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UNITED STATES DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
In cooperation with the Imperial Irrigation District

DRAINAGE INVESTIGATION IN IMPERIAL VALLEY, CALIF., 1941-51
(A 10-YEAR SUMMARY)

By
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FOREWORD

Drainage problems have invariably followed the introduction of irrigation to the arid and semiarid valleys of Western United States. Drainage in the Imperial Valley, Calif., has been one of the most vexatious of this region's problems.

Irrigation water was first brought to this Valley from the Colorado River in 1901. The fertility of the land and a favorable climate made for a rapid agricultural development of the region. However, extreme complexity of soils, including marked differences in the textural stratification through the profile, together with an abundance of slightly saline water, soon brought about a widespread need for drainage. As early as 1902, soil scientists,[1] and again in 1908 irrigation engineers,[2] of the United States Department of Agriculture called attention to this need, and in 1914 drainage investigations were recommended.[3] No funds were provided for such a study. By 1919, about one-fourth of the approximately 500,000 acres of irrigable land was affected in some degree by high water table and salt accumulation.

About 1921, after a survey by a consulting drainage engineer, the Imperial Irrigation District constructed an open drainage system at an estimated cost of $2,500,000. This system was only partially successful in draining the land, owing to a lack of understanding of the soil stratifications and their effect on the movement of water through the soil. Subsequent surveys showed that, in spite of these open drains, water-soluble salts were steadily accumulating in the Valley as a result of excessive salt intake in irrigation water and poor internal drainage of the soil. For nearly 20 years following the construction of the main open drains, Federal, State, and local agencies, including the Imperial Irrigation District, made surveys and investigations relating to this problem. The limited success of these investigations is shown by the fact that eventually the Federal Land Bank of Berkeley suspended the making of loans in many sections of the Valley, primarily because of the hazard of high water table and the lack of assurance that drainage would be successful. The Valley's agricultural credit was at stake.

In 1940, a meeting was called to discuss the problem. Present were farmers and representatives of the Imperial Irrigation District, the Soil Conservation Service, and the University of California. As a result of this meeting the Department of Agriculture, through the Soil Conservation Service, was requested to give assistance to the farmers of the Valley by cooperating in research and action programs with the Imperial Irrigation District.

An Imperial Valley Drainage Advisory Committee was formed. It was composed of representatives of the Soil Conservation Service (Research and Operations), Imperial Irrigation District, Farm Credit Administration, and the University of California. This committee functioned as a review board. It passed on the research and action program proposed by the Research and Operations technicians, heard the annual progress reports, and made suggestions for such modification as seemed desirable.

This procedure represented a marked departure from previous investigations and research. It created a team of Soil Conservation Service-Research technicians working closely with Operations technicians of the Soil Conservation Service and the Imperial Irrigation District, which took the findings of research and adapted them to farm practices. Through the efforts of the Advisory Committee for general planning and review, the Research technicians to establish the facts and develop methods for successful drainage, and the Operations technicians to put into practice the research findings, there has resulted in the short space of 10 years a practically complete solution of the drainage problem in the Imperial Valley. Tools, methods, procedures, and facts became available with which the Operations technicians could determine for any given farm:

1. Which lands were feasible and economical to drain.
2. The size and location of tile lines so as to provide maximum drainage.
3. Optimum depth and spacing of tile lines.
4. Leaching required to maintain salt balance in the soil.
5. Cropping system required for reclamation.

As a result of this cooperative research and action program, financed jointly by the Soil Conservation Service and the Imperial Irrigation District, more than 100,000 acres of land in the Imperial Valley have been successfully drained in the short space of 10 years, and the entire area is well along toward complete reclamation.

The value of these investigations is not limited to the Imperial Valley. Many basic principles and methods of analysis relating to drainage which have been developed are applicable to the drainage of irrigated land regardless of its location.

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[1] Means, T.H., and Holmes, J. G. Soil survey around Imperial California. U. S. Dept. Agr. Bur. Soils. 1902.

[2] Tait, C. E. Irrigation in Imperial Valley, California, its problems and possibilities. Senate Doc. No. 246, 1st Sess., 60th Congress. February 1908.

[3] Tait, C. E. and Veihmeyer, F. J. Report of general survey to determine cause and extent of water logging in Imperial Valley. U. S. Dept. Agr. 1914. [Typewritten.]

The purpose of this report is to present a condensed account of the work done and the results obtained from these investigations, in such form that it may be readily utilized by the personnel of the Imperial Irrigation District and the Soil Conservation Service in their farm-conservation planning program, and to make available to all who have drainage problems the experience and the results of these investigations.

George D. Clyde
Chief, Division of Irrigation Engineering
and Water Conservation
Soil Conservation Service--Research

Acknowledgments.--This investigation has been a joint endeavor participated in by all the cooperating agencies. The contributions made by the various administrative personnel of the Imperial Irrigation District, the University of California, the Federal Land Bank, and the Soil Conservation Service are gratefully acknowledged. Much of the material included in this report has been presented previously in various progress reports or in separate papers by individuals on the staff.

Acknowledgment is made of the assistance rendered by A. C. Bowen, W. H. von Trebra, Vern C. Miller, Alvin Oakley, Thomas Holmes, and John Shade, all at one time or another members of the Soil Conservation Service--Operations Imperial Valley Staff, who contributed helpfully in both the laboratory and the field.

Acknowledgment is given to E. W. Hartzog, Construction Superintendent for the Imperial Irrigation District; John T. Rice and Russell L. Trexlar of the Imperial Irrigation District's Laboratory; George Winright and staff of the Imperial County Farm Advisor's office; L. G. Goar, formerly of the University of California Meloland Experiment Station, and the staffs of the Regional Salinity Laboratory, Bureau of Plant Industry, Soils, and Agricultural Engineering, United States Department of Agriculture, and the Citrus Experiment Station, University of California.

V. S. Aronovici, Soil Scientist, conducted most of the research on soils and irrigation (1942-48); Willis C. Barrett was Project Leader the first 2-1/2 years; William W. Fox was Project Leader 1943-46; William T. Gish was Engineering Aid.

REPORT ON DRAINAGE INVESTIGATION IN IRRIGATED AREAS OF IMPERIAL VALLEY, CALIF., 1941-51

(A 10-Year Summary)[1]

By William W. Donnan, drainage engineer, George B. Bradshaw, associate irrigation engineer, and Harry F. Blaney, project supervisor, Division of Irrigation Engineering and Water Conservation, Soil Conservation Service--Research

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[1] Prepared under the direction of George D. Clyde, Chief, Division of Irrigation Engineering and Water Conservation, Soil Conservation Service--Research, U. S. Department of Agriculture. October, 1951.

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INTRODUCTION

The Imperial Valley drainage investigation was started in June 1941 as a result of recommendations made in April 1941 by a committee consisting of representatives of the Soil Conservation Service of the United States Department of Agriculture, the Farm Credit Administration, the University of California, and the Imperial Irrigation District. The investigation has been conducted since then by the Soil Conservation Service under the guidance of the Imperial Valley Drainage Committee, representing the above-named agencies. A memorandum of understanding between the Soil Conservation Service, the Farm Credit Administration, and the Imperial Irrigation District, executed in June 1941, states:

> "It is the purpose of this Memorandum of Understanding to establish a basis upon which the parties hereto may cooperate in a program of drainage investigations and operations in the Imperial Valley, Imperial County, Calif., with the objective of determining the most practicable means of maintaining and/or restoring the productivity of lands of Imperial Valley within the boundaries of the Imperial Irrigation District, which are, at present, or may, in the future, become unfit for agricultural use because of a high water table as a result of poor drainage."

The objectives of the study of the drainage problem of the Imperial Valley have been: (a) To establish criteria by which the feasibility of drainage on any lands within the Imperial Irrigation District may be determined; (b) to establish methods of designing and installing practical drainage facilities where drainage is feasible, and (c) to develop techniques for improving irrigation practices.

Several progress reports [2] [3] [4] [5] [6] have been made by the staff of the Imperial Valley drainage project.

Description of the Area

The Imperial Valley is located in the extreme southeast portion of California and includes almost all of the agricultural land in Imperial County (fig. 1). The investigation is concerned only with that land within the Imperial Irrigation District which extends north from the International Boundary about 45 miles to the Salton Sea and has an average width of about 25 miles.

The Valley is a graben which has been depressed gradually, and, at the same time, encroached upon by the Colorado River delta. During recent geological times the Colorado River has flowed alternately into the Salton Sea Basin, raising the level of the lake occupying it, and into the Gulf of California, permitting evaporation to shrink the lake. This has produced a wide deltaic ridge, with a maximum elevation of 40 feet above sea level, which closes off the Salton Sea Basin. The maximum depth of the basin is about 271 feet below Pacific sea level with the present Salton Sea level at 240 feet below Pacific sea level. Sediments brought from several States were deposited in varying locations, sequences, and thicknesses that depended upon the vagaries of the river and the fluctuations of the lake level.

It is assumed that the newly exposed sediments developed sun cracks each time the lake receded. Wind action may have filled these cracks with sand and may, in many instances, have built dunes upon them before the next inundation occurred. Thus, the formational elements were present for a highly complex body of stratified soil material, as well as for structural conditions that confuse the picture of soil-moisture relations. Such a body of soil material is present. But, some strata do exist that are consistent in thickness and continuous over an area of many acres.

Climatically, the Imperial Valley is characterized by low annual rainfall, low humidity, and high summer temperatures (table 1). The average date of the first killing frost in the fall is December 9, while the average date of the last killing frost in the spring is January 29.

All farming in Imperial Valley is done by irrigation, the annual precipitation of 3 inches being sufficient to support desert flora only. While the area is known to many only as a producer of lettuce and melons, the acreage devoted to those crops is much less than that in alfalfa and flax, and other crops (table 2).

Water for irrigation was first brought from the Colorado River in 1901. Presence of a large body of sand dunes on the American side of the

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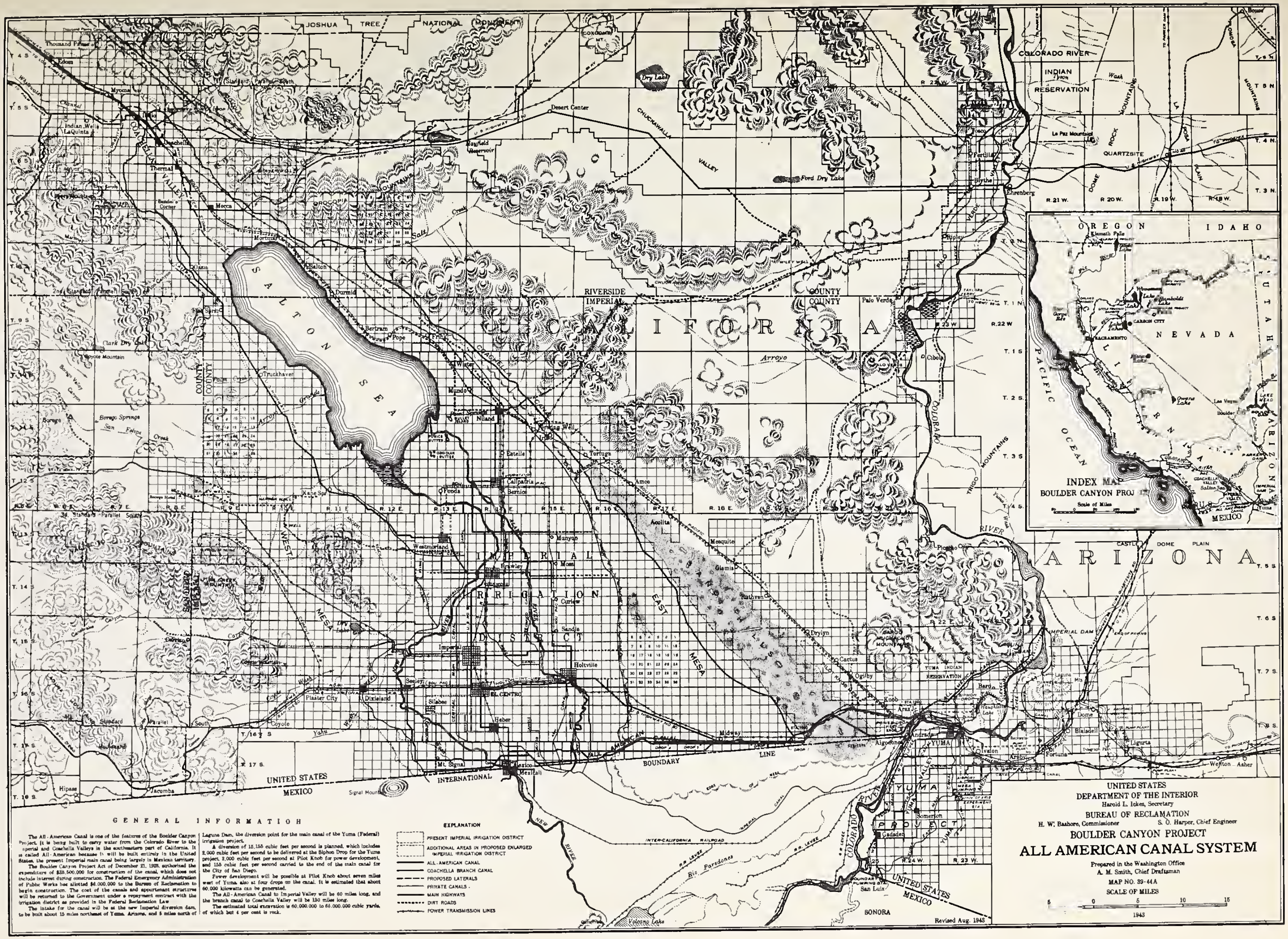
[2] Barrett, W. C. Imperial Valley drainage investigations progress report. May 1942. [Typewritten.]

[3] Barrett, W. C., Imperial Valley drainage investigation progress report. March 1943. [Typewritten rough draft.]

[4] Fox, W. W., Aronovici, V. S., and Donnan, W. W. Imperial Valley drainage investigation progress report, 1943-1944. October 1944. [Mimeographed.]

[5] Fox, W. W., Aronovici, V. S., and Donnan, W. W. Imperial Valley drainage investigation progress report 1944-1945. October 1945. [Typewritten.]

[6] Donnan, W. W., Aronovici, V. S., and Blaney, H. F. Report on drainage investigation in irrigated areas of Imperial Valley, California. January 1947. [Mimeographed.]



GENERAL INFORMATIOH

The All-American Canal is one of the features of the Boulder Canyon Project. It is being built to carry water from the Colorado River to the Imperial and Coachella Valleys in the southeastern part of California. It is called All-American because it will be built entirely in the United States, the present Imperial main canal being largely in Mexican territory.

The Boulder Canyon Project Act of December 21, 1928, authorized the expenditure of $38,500,000 for construction of the canal, which does not include interest during construction. The Federal Emergency Administration of Public Works has allotted $4,000,000 to the Bureau of Reclamation to begin construction. The cost of the canals and appurtenant structures will be returned to the Government under a repayment contract with the irrigation district as provided in the Federal Reclamation Law.

The intake for the canal will be at the new Imperial diversion dam, to be built about 15 miles northeast of Yuma, Arizona, and 5 miles north of Laguna Dam, the diversion point for the main canal of the Yuma (Federal) irrigation project.

A diversion of 15,155 cubic feet per second is planned, which includes 2,000 cubic feet per second to be delivered at the Siphon Drop for the Yuma project, 3,000 cubic feet per second at Pilot Knob for power development, and 155 cubic feet per second carried to the end of the main canal for the City of San Diego.

Power development will be possible at Pilot Knob about seven miles west of Yuma, also at four drops on the canal. It is estimated that about 60,000 kilowatts can be generated.

The All-American Canal to Imperial Valley will be 80 miles long, and the branch canal to Coachella Valley will be 130 miles long.

The estimated total excavation is 60,000,000 to 65,000,000 cubic yards, of which but 4 per cent is rock.

Figure 1.--Location of the Imperial Valley, Calif.

TABLE 1.--Mean monthly temperatures and precipitation for period of record at Brawley, Imperial, El Centro, and Calexico Weather Bureau stations

Month	Brawley[1]		Imperial[2]		El Centro[3]		Calexico[4]	
	Temperature	Precipitation	Temperature	Precipitation	Temperature	Precipitation	Temperature	Precipitation
	°F	*Inches*	°F	*Inches*	°F	*Inches*	°F	*Inches*
January	53.1	0.34	54.1	0.30	54.2	0.28	53.4	0.46
February	55.9	.41	58.2	.79	66.3	.61	58.0	.48
March	62.3	.21	64.3	.22	64.2	.29	63.4	.28
April	69.7	.13	70.4	.17	70.4	.10	69.8	.09
May	77.2	.05	77.6	.02	7.84	.00	74.6	.05
June	84.9	.01	84.8	.00	84.5	.01	84.2	.01
July	91.3	.05	91.7	.09	92.4	.09	89.6	.08
August	90.8	.24	90.9	.36	90.5	.27	89.2	.56
September	84.6	.28	84.2	.51	86.2	.50	83.4	.22
October	73.1	.23	73.8	.23	75.1	.24	72.4	.15
November	61.4	.14	61.9	.15	62.8	.10	61.4	.27
December	53.8	.64	55.0	.87	56.1	.74	52.9	.46
Total or mean	71.6	2.73	72.2	3.71	72.9	3.23	71.0	3.11

[1] Mean for 34 years' record.
[2] Mean for 25 years' record.
[3] Mean for 14 years' record.
[4] Mean for 20 years' record. (1904-24)

TABLE 2.--Approximate acreage of principal crops grown in Imperial Valley, Calif.

Year	Alfalfa	Flax	Barley	Vegetables	Wheat	Sugar Beets
	Acres	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*
1941	118,000	98,000	56,000	69,000	4,000	7,000
1942	116,000	106,000	52,000	66,000	5,000	8,000
1943	114,000	145,000	33,000	55,000	1,000	8,000
1944	147,000	62,000	71,000	66,000	1,000	5,000
1945	159,000	55,000	73,000	52,000	1,000	8,000
1946	160,000	54,000	67,000	64,000	1,000	12,000
1947	154,000	66,000	61,000	57,000	2,000	27,000
1948	109,000	134,000	58,000	52,000	4,000	41,000
1949	128,000	131,000	61,000	48,000	11,000	19,000
1950	164,000	49,000	62,000	49,000	33,000	34,000

International Boundary and a natural channel on the Mexican side resulted in choice of the Mexican route for the main canal. That route was used until the 80-mile All-American Canal was completed in 1942. The All-American Canal brings water to the southern end of the Valley. It is taken northward by 3 main canals, which branch into a network of distributaries delivering water to the high corner of each 160-acre tract.

The 1,700 miles of irrigation canal (excluding a portion of the All-American Canal) are owned and operated by the Imperial Irrigation District. Water costs are low in comparison with those in most parts of southern California.

The Imperial Irrigation District includes within its boundary some 900,000 acres of land and is equipped to deliver water to over 600,000 acres, with prospects of irrigating additional acreage from the All-American Canal. It has expended approximately $4,000,000 on the construction, operation, and maintenance of about 2,000 miles of open drains ranging in depth from 6 to 14 feet.

Fortunately, the Colorado River incursion of 1905 enlarged the channels of the New and Alamo Rivers enormously, and they now act as main drainage trunks, carrying the flow from the drainage ditches to the Salton Sea.

The Problem

Prior to 1941 some irrigable lands of the Imperial Valley had become so waterlogged and impregnated with salts as to become unprofitable for agriculture. Drainage methods that had been successful in areas of homogeneous soils were not adaptable to the stratified alluvial and lacustrine soils. The Colorado River water contains approximately 1 ton of salts per acre-foot; thus, the problem of using saline water for irrigation was also involved.

While many farms were protected in various degrees against rise of the water table by the installation of tile lines, the owners of other farms were hesitant to invest in similar facilities because they could not be certain of results.

Many approaches to scientific tile-drain design have been reported in the literature. None of them, however, could be directly applied to the Imperial Valley for several reasons: (1) The stratified soils, with unusual structural features, could not be treated in the same manner as homogeneous soil bodies. (2) Heavy soils with low permeabilities were common. (3) The ground water was usually too saline for plant use, necessitating deep drainage to minimize continuous rise of moisture from the water table into the upper root zone or ground surface. (4) The soils were saline. (5) Water movement downward into and through the soil profile must exceed plant requirements to maintain a favorable salt balance. Thus, to accomplish the objective of the Imperial Valley Investigation, it has been necessary to devise new techniques. During the progress of the study, a continual search had been made for means of simplifying procedures.

Previous Investigations

The United States Department of Agriculture and the Agricultural Experiment Station of the University of California have made investigations in Imperial Valley at various times since 1901.

Beginning in 1901 the Bureau of Soils of the United States Department of Agriculture and the Agricultural Experiment Station of the University of California made several soil surveys of Imperial Valley. The experiment station also made studies of reclamation of alkali soils and drainage. A soil salinity study on several test plots has been conducted by the University of California Citrus Experiment Station for a number of years.

The Division of Irrigation (Irrigation Investigations) made cooperative investigations on irrigation and sedimentation, 1907-08; wells and water levels, 1913; seepage and drainage, 1914; irrigation requirements, 1915-17; sedimentation, 1917-27; and water supply, irrigation, and drainage, 1933.

For many years the Bureau of Plant Industry of the United States Department of Agriculture accumulated data on salinity of Colorado River water.

Long-period ground-water records have been kept of numerous observation wells by the Imperial Irrigation District. A mass of other information on drainage and irrigation has been recorded by the District since it was organized in 1915.

Definition of Terms

Apparent specific gravity (volume weight). The ratio of the ovendry weight of a given volume of soil, pore space included, to the weight of an equal volume of water at a temperature of 4° C. (ASAE)[7]

Aquiclude. A sediment or soil which, although capable of absorbing or adsorbing water will transmit water very slowly.[8]

Aquifer. Water-bearing formation through which water moves readily in comparison with the movement through formations of low permeability such as clays. (ASAE)

Barrier. A sediment or soil which absorbs water very slowly and greatly restricts or prevents any appreciable flow of water through it.

Capillary fringe. The subsurface zone immediately above a water table and within the zone of aeration in which the moisture content is in excess of the field capacity. (ASAE)

Coefficient of permeability. The rate of flow of water through a unit cross-sectional area with a unit head. This may be expressed in cc. per. sq. cm. per hour or gallons per sq. ft. per day. Sometimes called transmission constant.

Consumptive use (evapotranspiration). The sum of the volumes of water used by the vegetative growth of a given area in transpiration or building of plant tissue and that evaporated from adjacent soil, snow, or intercepted precipitation on the area in any specified time, divided by the given area. If the unit of time is small, such as a day or a week, the consumptive use is expressed in acre-inches per acre or depth in inches; whereas, if the unit of time is large, such as a crop-growing season or a 12-month period, the consumptive use is expressed as acre-feet per acre or depth in feet. (ASAE) (SCS)[9]

Desorption curve. A graphic representation of the water-holding capacities of a sediment or soil against a series of increasing tensions. Usually the ordinant is expressed in centimeters tension of water or mercury and the absisa in percent water by volume.

Drainage. (1) The process of removing surplus ground or surface water by artificial means; (2) the manner in which the waters of an area are removed; (3) the area from which waters are drained; a drainage basin. (ASCE)

Draintile. Pipe of burned clay, concrete, etc., in short lengths, usually laid with open joints to collect and remove drainage water. (ASCE)

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[7] Authority: American Society of Agricultural Engineers; American Society of Civil Engineers.

[8] Authority: C. F. Tolman.

[9] Authority: Soil Conservation Service.

Duty of water. The quantity of irrigation water applied to a given area for the purpose of maturing its crop, expressed as acre-feet or acre-inches per acre or as depth in feet or inches.

Effluent. Seepage of ground water out to a drain or stream. (CFT)

Field capacity. The moisture percentage, on dry weight basis, of a soil after the rapid drainage, following an application of water, has taken place. (ASAE)

Ground water. The water in the zone of saturation.

Hydraulic gradient (or hydraulic slope). The ratio of the loss is the sum of the pressure head and position head to the flow distance. For open channels it is the slope of the water surface. (ASAE)

Infiltration. The flow or movement of water into the soil. Rate of infiltration may be expressed in depth of water per unit time or flow per unit area. (ASAE)

Irrigation efficiency. The percentage of irrigation water delivered to the farm or field that is available in the soil for consumptive use by the crops. When measured at the farm headgate it is called farm-irrigation efficiency, and when measured at the field or plot it is designated as field-irrigation efficiency. (SCS)

Irrigation requirement. The quantity of water, exclusive of precipitation, that is required for crop production. It includes surface evaporation and other economically unavoidable wastes. Usually expressed in depth for given time (volume per unit area for given time). (ASAE) (ASCE)

Leach. To remove soluble materials from the soil in solution by applying excessive quantities of water. May require artificial drainage.

Length of run. The distance water must travel in furrows or over the surface of the field from the head ditch to the end of the field.

Macro-stratification. A series of layers within the sediment or stratum which is visible only by close observation or use of a hand lens.

Moisture equivalent. The percent of water by weight retained by soil when subjected to centrifugal force of 1,000 gravity.

Percolation. Movement of water through the interstices of a substance, as through soils. (ASCE)

Permeameter. Equipment designed to measure the coefficient of permeability.

Permeagraph. A graphical representation of the relative coefficient of permeability of a strata-survey boring.

Piezometer. A small diameter observation well which has been sealed off from the hydrostatic pressure of the ground water at all points except the tip end.

Seepage. The loss of water by infiltration from a canal, reservoir, or other body of water, or from a field. It is generally expressed as flow, volume per unit time. (ASAE)

Soil moisture (capillary moisture). The water in unsaturated soils. Usually expressed as a percentage on the dry-weight basis, or in inches per foot depth of soil. (ASAE)

Specific retention. The amount of water that a unit volume of permeable rock or soil, after being saturated, will retain against the force of gravity when drained. It may be expressed as a ratio or as a percentage of volume. (ASAE)

Waterlogging. The replacement of most of the soil air by water due to the rise of the water table, either continuously or during periods of time long enough to be injurious to some plants, or to the soil as the result of alkali accumulation near the surface. Waterlogging is essentially due to inadequate drainage and may be increased by overirrigation, seepage from canals or higher lands, excess rainfall, or a combination of these factors.

Water table. The upper boundary of the zone of saturation, except where bounded by an impervious stratum. A surface where the hydrostatic pressure is equal to the atmospheric pressure, as determined by the water level in open wells that barely penetrate the zone of saturation. (ASAE)

Zone of aeration. Subsurface zone above the water table in which the soil or permeable rock is not saturated, or if saturated, where the hydrostatic pressure is less than atmospheric. (ASAE)

Zone of saturation. Subsurface zone below the water table in which the soil or permeable rock is saturated with water under a pressure greater than atmospheric.

INVESTIGATIONS 1941-43[10]

One of the earliest accomplishments of the drainage investigation was to utilize some of the voluminous information recorded by the Imperial Irrigation District over a period of many years.

Water-Table Observations[11]

Observation wells for a study of the water table were first installed by the Imperial Irrigation District in 1920. By 1930 there were some 780 wells in roughly a 1-mile grid over the major part of the irrigated area. Each well consisted of a 2-inch galvanized iron pipe 8 feet long. The observation hole was bored to a depth of 15 feet. Thus, only the upper 8 feet were cased and the wells were rebored frequently to reopen the lower 7 feet. An observation was made at each well every 3 months.

Three water-table maps of Imperial Valley were compiled from records of these well observations and represent the best available data on the trend of the water-table fluctuations from 1930 to 1943. The data from which these maps were compiled have many limitations. Wells were located, for the most part, near drains or canals and in corners of fields. Cropping practices varied from year to year. Some wells tended to clog and lacked sensitivity. The maps do indicate a broad trend in the overall water-table position, however. The September reading of the wells was used in each case to compile the maps because it reflected the most reliable relative level in the yearly cycle. Finally, all well recordings are tabulated with reference to the ground surface and thus are not to be construed as part of a basic water-table level over the entire valley. They may represent perched tables that may or may not be interconnected.

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[10] Investigations conducted by Willis C. Barrett, W. W. Fox, W.W. Donnan, and V. S. Aronovici, 1941 and 1942, under the supervision of Harry F. Blaney.

[11] See footnote 2, p. 2.

The September 1930 map shows the water table to be a menace and, although the indication is spotty, it discloses where the general problem areas were forming. The 1940 map represents perhaps the apex of the water-table trend.[12] Maps compiled for intervening years indicate a progressive rise of the water table to 1940. The 1940 map (fig. 2) shows a spreading and enlarging of the high water-table areas in spite of a considerable increase in drainage facilities during the 10-year period. One reason for the high water table of 1940 is that the excessive canal erosion of that year, due to the introduction of desilted water from the All-American Canal, may have aggravated seepage from the canal-distribution system. The 1943 observations show a trend towards an improved condition of the overall water-table elevation.

A comparison of the observations in September 1930, 1940, and 1943 reveals that the spotty evidence of high water table that was apparent in 1930 had increased considerably by 1940, but that by 1943 the water table had receded in some areas and showed marked improvement. A rough estimate of the amount of improvement in 1943 over the 1940 water table was obtained by tabulating the wells for those 2 years according to the 3 depth classifications. The results were as follows: [13]

Depth	Percentage	
	1940	1943
0 to 6 feet	43.7	30.0
6 to 8 feet	20.5	28.9
Below 8 feet	35.8	41.1

"This improvement is attributed to the following factors:

"(1) Better water distribution. The canal grades have been cut down and the cross sections widened out to slow up the velocities and prevent cutting. This tends to create a seal to the canals which it has not been necessary to break or disturb in cleaning operations heretofore necessary with the silty water. There has been a recession in the amount of canal seepage. Many seepage-interception drains are drying up, and road-ditch tule beds are disappearing.

"(2) Canals are more deeply entrenched with respect to the general ground level. In the stabilization process attendant upon the use of clear water, many canals have entrenched and are not flowing on high silt crests, as was the case prior to 1941.

"(3) Better irrigation practices. This includes better land leveling, of which a great amount has been done by landowners since the boom of agriculture.

"(4) A mass installation of surface-waste outlets at the lower ends of fields, also accelerated by the desire of landowners to improve their holdings with the recent increased profits.

"(5) The system of drain ditches being dug by the District is constantly being improved, deepened, and expanded in attempts to provide an outlet to every 160 acres of land. Private drains are being installed at a rate of 30 to 40 miles a year, and tile installation is being made at the rate of 50 miles a year.

"All these factors are contributory to a favorable trend in the overall water-table elevations in the Valley. No evidence can be found that there has been any recession in the intensity of land use during this improvement period; in fact, there may have been a slight increase in double cropping.

"Conclusion. The improvement shown by the 1943 map of the water table is very encouraging and perhaps the causes for this improvement should be more fully analyzed. However, the improvement shown here does not indicate that the water-table problem has been solved. It only serves to emphasize that there is still a definite problem in spite of the tremendous amount of effort expended to remedy the situation. It also indicates that getting at the source of the problem by better use of water is one of the most significant factors in the overall drainage picture."

Study of Existing Tile Systems

Early in the investigation data were compiled for all tile lines installed and the soil series involved. Tile layout maps were obtained from the district. Properties in which the layout was extensive but of regular design, and where the soil distribution was not complex, were selected for study.

Farm owners or operators of the properties were interviewed. Factors considered were soil series, age of the installation, and the presence or absence of a bedding of gravel placed around the tile. Effectiveness of the installation was graded as "excellent," "good," "fair," or "poor" on the basis of the farmer's opinion; that is, whether he considered the tile properly spaced, the amount of improvement of crops, the decrease in alkali concentration where evidence existed, and similar considerations. The results of the 1941 survey are tabulated in table 3. Table 4 has been prepared from data shown in table 3.

A tabulation of the relation of age to effectiveness of tile drains is shown in table 5.

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[12] See footnote 2, p. 2.

[13] See footnote 4, p. 2.

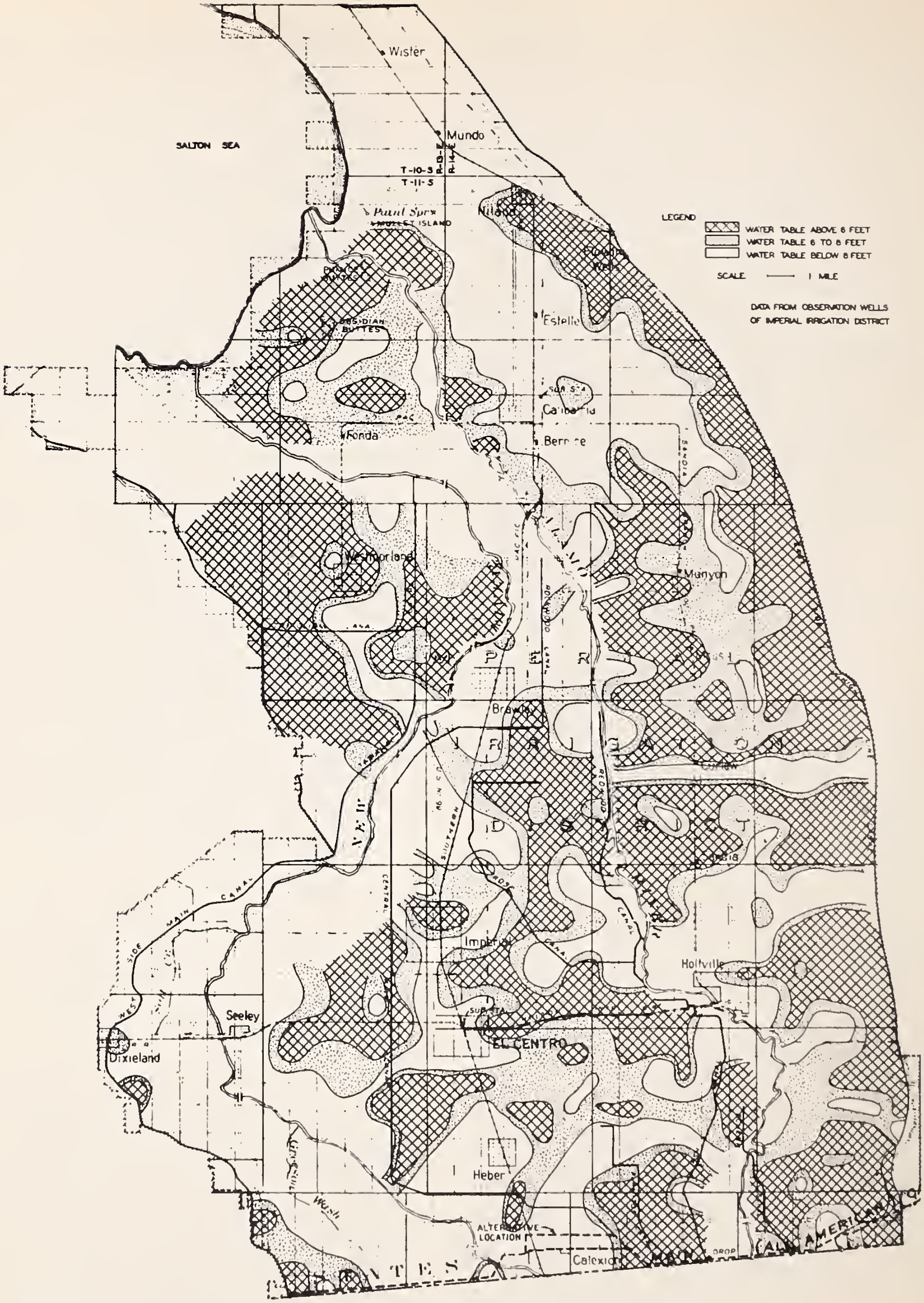

Figure 2.--Position of water table, September 1940, Imperial Valley, Calif.

TABLE 3.--Effectiveness of tile drains in operation, as shown by farm contact-reports, Imperial Valley, Calif.

Name of owner	Soils	Age in years	Gravel protected	Effectiveness			
				Excellent	Good	Fair	Poor
Bridgers................	(Rositas	1	Yes		x		
	(Meloland				x		
Brownell................	Imperial	10	No			x	
Chambers................	Holtville	9	No		x		
Christian...............	Meloland	2	Yes		x		
Dogett..................	Meloland	3	Yes	x			
Fleming.................	(Superstition	12	No	x			
	(Niland			x			
	(Holtville					x	
Harshman................	Dune Sand	2	Yes	x			
Holtville Orch. Co......	Holtville	11	No				x
Homola..................	Dune Sand	3	No	x			
Lindsay.................	Holtville	2	Yes		x		
Mallory.................	(Rositas	3	No		x		
	(Imperial	3	No				x
McBride.................	(Meloland	2		x			
	(Rositas			x			
Mets....................	(Holtville	4	No	x			
	(Meloland						
	(Rositas						
Scott...................	Meloland	3			x		
	(Holtville	3		x			
	(Imperial					x	
Stahman.................	(Rositas	4	No	x			
	(Meloland			x			
Steiner.................	Imperial	1	Yes		x		
Young...................	(Imperial	1	Yes		x		
	(Holtville						
	(Meloland						
	(Superstition						
	(Niland						
Totals				11	9	3	2

TABLE 4.--Relation of soil series to effectiveness of tile drains, Imperial Valley, Calif.

Soil series	Excellent	Good	Fair	Poor	Number of samples
	Percent	*Percent*	*Percent*	*Percent*	
Imperial................................	--	40	40	20	5
Holtville...............................	33	33	17	17	6
Meloland................................	50	50	--	--	6
Rositas.................................	50	50	--	--	4
Dune Sand...............................	100	--	--	--	2
Superstition............................	100	--	--	--	1
Niland..................................	100	--	--	--	1

An attempt was made to draw conclusions from observations and opinions of the farmers interviewed. Briefly the conclusions were as follows:[14]

"(1) Tile drains, in general, have given results that are satisfactory to the farmers.

"(2) Tile drains have been most satisfactory to the farmers when installed in dune sand or soils of the Superstition and Niland series and least satisfactory in Imperial soils. The Holtville, Meloland, and Rositas series occupy an intermediate place.

"(3) Recent installations are generally better than old ones. This may be due in part to improved installation techniques and in part to deterioration and clogging of the older lines.

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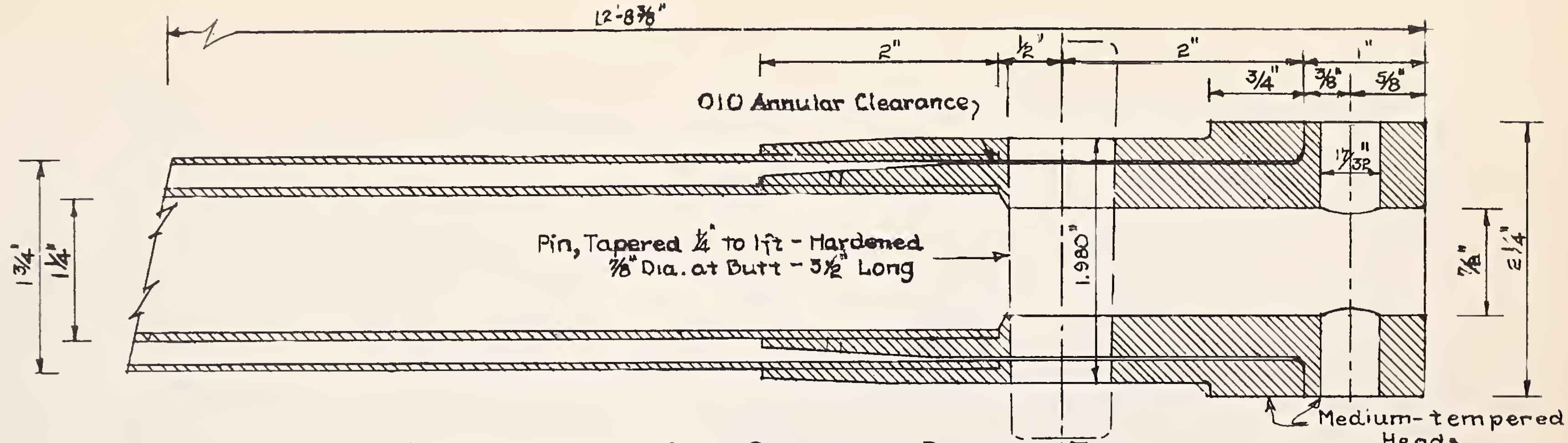
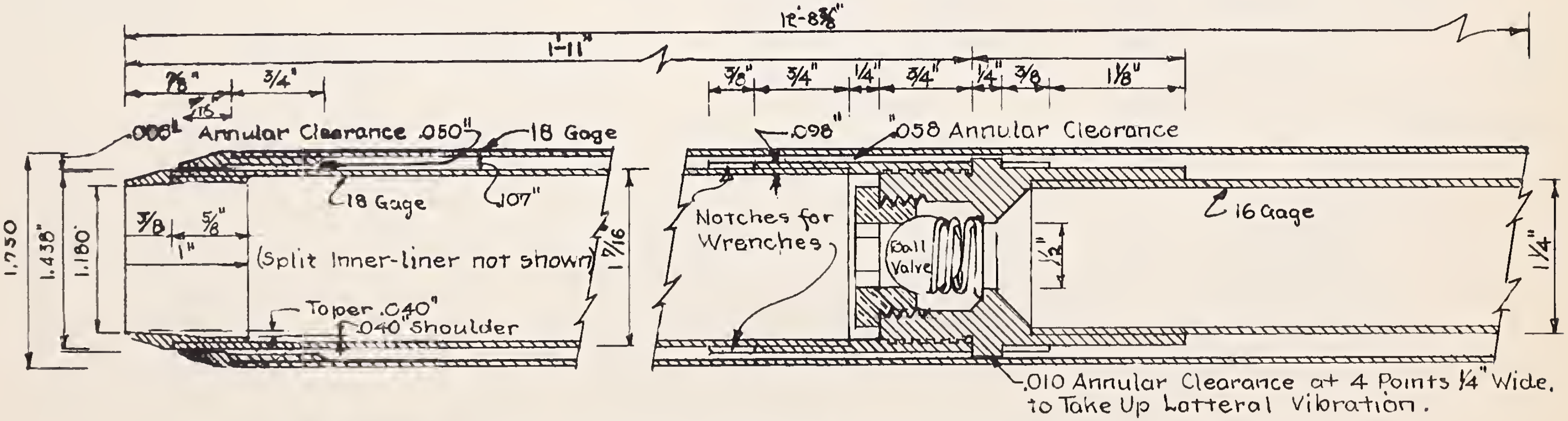
[14] See footnote 4, p. 2.



LONGITUDINAL SEC. SHOWING DRIVING END



LONGITUDINAL SEC. SHOWING INNER CORING-CYLINDER
(SCALE: NATURAL SIZE)

NOTE: Tubing to be crome-moly steel.
Fittings to be crome-nickle, crome-vanadium, or nickle steel.
All rigid joints to fit with clearance of .010"+/- for brazing or soldering.

Figure 3.--Imperial Valley, Calif., soil-sampling tube.

TABLE 5.--Relation of age to effectiveness of tile drains, Imperial Valley, Calif.

Age in years	Year installed	Number of installations			
		Excellent	Good	Fair	Poor
1	1940	--	4	--	--
2	1939	3	2	--	--
3	1938	3	2	1	1
4	1937	3	--	--	--
5	1936	--	--	--	--
6	1935	--	--	--	--
7	1934	--	--	--	--
8	1933	--	--	--	--
9	1932	--	1	--	--
10	1931	--	--	1	--
11	1930	--	--	--	1
12	1929	2	--	--	--

"(4) A gravel envelope around the lines increases tile effectiveness."

The survey of tile-system efficiency was followed in 1942 by cursory field studies of tile flow and attempts at correlation of flow with tile spacing and with soils.

Tile-Durability Study

At the request of the Imperial Valley Drainage Committee and by benefit of funds provided by the Imperial Irrigation District and other interested parties, Dalton G. Miller, Senior Drainage Engineer, Division of Drainage, Soil Conservation Service, St. Paul, Minn., made a limited field investigation of tile durability in Imperial Valley in February, 1943. Fifteen days were spent in the field gathering tile samples and making observations of tile lines and concrete emplacements. A number of tile samples were run through a brake-testing machine, and samples were shipped to the St. Paul laboratory where freezing and thawing tests were made. The results of this investigation were presented in a report,[15] a summary of which follows:

"Soil conditions throughout the district are about borderline in regard to probable deleterious action of soil alkalies on concrete draintile. As a consequence, they should be installed only after the salinity of the subsoil to which the tile will be exposed has been determined. If, from these examinations, it appears probable that soil waters which carry an excess of around 10,000 p. p. m. of total salts will be in contact with the tile, the advisability of using concrete tile is of questionable economy. The quality of any concrete draintile used in the district should be of the highest order. Concrete tile can be made which will have high sulfate resistance, provided the following recommendations are rigidly followed:

"(1) Make concrete of unit compressive strengths upward from 5,000 pounds per square inch.

"(2) So proportion the mix that the water absorption will be under 6.0 percent when made by drying fragments of the tile to constant weights in an oven at 230° F. and boiling for 5 hours.

"(3) Following moist curing, harden in air for at least 30 days previous to installation.

"(4) Most important of all, use only sulfate-resisting cement closely conforming to the requirements of the A. S. T. M. Type V.

"The La Bolsa clay tile from the plant at Huntington Beach is a surface clay product. The average output from this plant just about meets the American Society of Testing Materials' physical requirements for standard draintile. It is believed that this product will satisfactorily withstand the soil alkalies to which they will be subjected after installation in the district. Tile from this plant should not be loaded in excess of 1,200 pounds per linear foot . . . . ."

Imperial Valley Soil-Sampling Apparatus

Since one of the major tasks confronting the investigation was to study subsurface soils, several types of soil-sampling equipment were tested. Tests demonstrated that, in saturated soil, augers and the standard soil tubes were unsatisfactory for obtaining cores of undisturbed soil for laboratory analysis and study. Therefore, a special soil-sampling apparatus was designed by Willis C. Barrett (fig. 3). It employed a multiple tube driven by an air jackhammer from the back of a 1-1/2 ton truck. An A-frame was mounted on the truck for a hammer suspension and to support a ratchet hoist that was used in pulling the tubes (5).[16]

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[15] "Report of Drain Tile Durability Studies in the Imperial Irrigation District, California."

[16] Numbers in parentheses refer to Literature Cited.

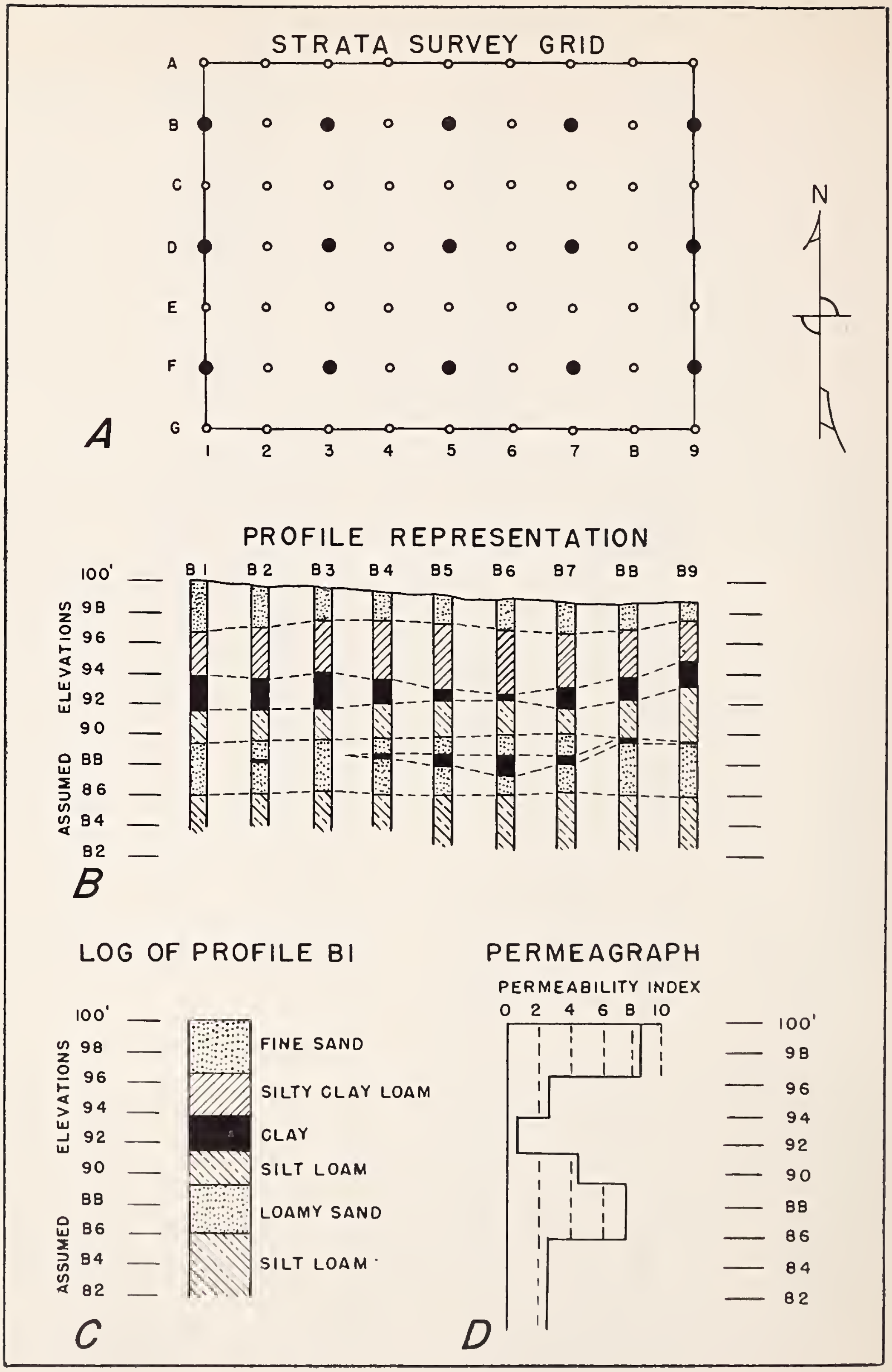

Figure 4.--Stratum survey grid, profile, log, and permeagraph.

INVESTIGATIONS 1943-47[17]

The early work of the project revealed (1) that the problem could not be solved by analysis of the large volume of existing data; and (2) that principles of drainage design developed primarily for humid areas were not directly applicable to Imperial Valley conditions. During the preliminary phases of the investigation, work was started to develop the principles of stratum surveying, streamline flow, and permeability measurement. These experiments turned the emphasis of the work toward the fundamentals affecting the drainage of subsurface water.

The Darcy Law

The fundamental law pertaining to the flow of water through the capillary interstices of saturated porous media is generally called Darcy's law (3). The hydraulic permeability of a porous material is its characteristic property of transmitting water through its interstices. The degree of this property has been designated by different names and has been expressed by various combinations of units of space and time. In this report it is called the "coefficient of permeability." The formula put forth by Darcy was expressed in the following form:

$$v = \frac{Ph}{L}$$

where v = velocity of water through a column o soil

h = the differential head

L = coefficient of permeability

This formula was later expressed in terms of quantity, and in its more familiar form has become (19):

$$Q = P\ I\ A$$

where Q = quantity of water discharged per unit of time

P = coefficient of permeability

I = hydraulic gradient

A = cross-sectional area through which the water moves

If the four factors Q, P, I, and A can be measured, almost any drainage condition can be analyzed, and a remedial measure can be designed to correct it. The following discussion deals with the methods used to measure these factors in Darcy's law and describes modified procedures.

The Stratum Survey

In keeping with the fundamental theory that the problem of land drainage in the Imperial Valley may best be approached by the solution of factors contained in the basic formula $Q = P\ I\ A$, the primary and most tangible factor for analysis is that of the cross-sectional area (A) or the dimensions of the material in which water movement takes place. This is accomplished through the "stratum survey."

A soil survey of the Imperial Valley was made in 1918 by the Bureau of Chemistry and Soils (11, 17). Four main soil series were established for the valley floor on the basis of holes 6 feet deep as follows:

	Rositas	Holtville	Imperial	Meloland
Surface	Light	Heavy	Heavy	Light
Subsoil	Light	Light	Heavy	Heavy

However, the problems of land drainage in the Imperial Valley also involve the characteristics of the material underlying this classified zone. Considerably greater detail within the 6-foot depth, not reflected in the general soil series, is likewise of vital importance. The nature of the water-transmission factors of the strata implies a need for information on the character and sequence of materials at depths of from 12 to 18 feet Inconsistencies and lack of surficial indication of the subsurface stratification reduce the value of the conventional soil survey. Moreover, since the 1918 survey, surface textures in many cases have changed owing to the deposition of very fine sand, silt, and some clay on the land from the sediment-laden irrigation water.

The solution of drainage problems requires an accurate evaluation of the elevations, thickness and sequences of stratification, and of the exture and structure of these materials. It was ecessary, therefore, to devise equipment which would take undisturbed samples of material when saturated or under hydrostatic pressure. It also became necessary to devise a systematic method of boring, logging, and classifying the soils.

Method of exploration

The degree of detail required of the stratum survey depends upon the conditions encountered and the character of the information sought. The number of borings required can be determined only after drilling has been started. A grid system is first surveyed with drilling points 100 to 400 feet apart. Elevations are determined at each drill point. The east-west traverses are designated by letters and the north-south lines by numbers (fig. 4). Random borings have little value in most drainage investigations. With the grid system, it is possible to limit borings to the extent of desired detail. When more detail is needed the grid may be covered more completely. For example in figure 4,A and 4,B, borings B-1, B-3, B-5, B-7, and B-9 provided all desired detail on the profile. Had they not done so, it would have been very simple to drill B-2, B-4, and B-6 without any confusion in numbering and locating the borings.

This system has proved satisfactory for field operations and related laboratory analysis. When an individual problem such as canal seepage is studied, single lines of borings may be made, but in all cases they are placed on an axis.

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[17] Investigations conducted by W. W. Fox, W. W. Donnan, and V.S. Aronovici under the supervision of Harry F. Blaney, Project Supervisor.

The recording of the logs is done at the time of drilling so that the samples are undisturbed and have not dried out when examined. A log sheet is used for recording information.

Selection of the type of equipment to be utilized in logging the stratum sequences should be guided by the degree of refinement desired in the results. Research work carried on during the first investigational work in the Imperial Valley required accurate sampling to a minimum depth of 16 feet. Because of the slow coverage rate, it became necessary, under the expanded program, to augment the drilling equipment with the standard soil auger and soil tube, and to compromise on a depth of 9 feet with occasional deeper borings.

Graphic representation of data

Since the usual land-surface map is not enough for graphic representation of the stratum survey, several methods of plotting data have been developed The procedure most generally used is to plot profiles (fig. 4, B). Subgrade topographic maps are used occasionally where the elevation of a continuous aquifer or barrier bears directly upon the problem under study.

Two methods of expressing the conditions found in the individual borings have been employed. Columns with colors representing the material encountered, plotted to vertical scale, have been used extensively. This method has the advantage of permitting an individual stratum to be traced by lining up the borings of a given axis to form a cross section (fig. 4, B). The other method, which is more useful, was developed on the principle that the whole stratum-survey objective, in final analysis, is the interpretation of the nature of the strata as related to water movement. After considerable field-and laboratory-permeability investigation, it was possible to interpret roughly the field characteristics of the strata in terms of comparative permeability. This value is the summation of all notes and observations made on the spot. All materials are classified into 11 general groups from 0 to 10. The values of these groups are outlined in the following section. When this permeability rating is plotted against depth, the resulting chart is termed a permeagraph (fig. 4, C).

The estimated values lose considerable significance when the survey work is accomplished in the main by the soil auger. Textures of various layers become mixed, especially when the ground is wet or saturated. Structures are very much less distinguishable. The permeagraph, therefore, becomes very much less significant as a field index. Soil color, general texture, stratum sequences, and association with adjacent borings are more reliable indices of the dimensions of the aquifer. Consequently, it is prudent to utilize the permeagraph with caution and rely more upon the other visual factors as a guide in plotting out the aerial distribution and sequence of stratification.

Of chief concern in drainage investigations is the character of the material as related to the movement of water. Tolman (18) has classified material into three general groups which are: "aquifer," material which will transmit water freely; "aquiclude," material which will transmit water very slowly; and "aquifuge," material which neither absorbs nor transmits water. None of the strata concerned conforms exactly to Tolman's "aquifuge," so the term "barrier" is substituted to indicate strata which definitely retard or restrict the movement of water. These terms are used to give a broad description of the transmissibility of the various strata.

Structures and texture

It is difficult to consider texture and structure separately in the study of permeability; therefore, discussions of these factors will be combined. Textural determination of the fine materials is dependent upon the combination of the component grain sizes, namely, sand, silt, and clay. For example, a true silty clay loam seldom occurs in the Imperial Valley. Careful examination of material designated by mechanical analysis as silty clay loam, clay loam, or silty clay will show that frequently the material is composed of microscopic stratifications of very fine sand, silt, and clay. Often a clay matrix is shot through with stringers, lenticles, or pendants of the coarse material. The results, then, from a mechanical analysis, will depend upon the percentages of each of the component parts and will give a distorted texture concept. Figure 5 illustrates the major types of structure found in the heavier textured materials. The sandy clay, not common in the Valley, is usually an exception to the rule and is thoroughly mixed.

The clay, when not accompanied with interlaminations of the fine sand and silt, is extremely compact, and usually is reddish or occasionally bluish-gray in color. This clay group frequently has iron stains which follow along bedding planes or vertically through fractures and root holes. Solution cavities containing crystallized salts often occur. The heavy-textured materials are strongly flocculated. Considerable difficulty has been encountered in deflocculation for mechanical analysis until all the dissolved salts are removed from the solution. Sandfilled fissures that range from a fraction of an inch to several inches in width and a few inches to several feet in length are found occasionally in the clay materials. These irregularities usually occur where there is a considerable thickness of clay overlain by extensive layers of sand. Fissures of this type are due to clay cracking when exposed on the surface and the subsequent washing or blowing of the sands into the cracks.

Investigations also revealed the presence of significant barrier-like structures. They are formed by lenses of the more permeable material overlying less permeable sediments, usually silty clay or clay, of irregular subsurface relief. When a condition of this nature exists on lands with some ground-surface slope, as along the valley side of the East Highline Canal, a special drainage problem may occur. Such stratigraphy is extremely important in planning a drainage facility. Ground water flows downslope along the top of the less permeable sediments. It may be forced toward the ground surface, or accumulate just above the line at which the barrier rises to or near the surface. Often, these barrier zones may be traced by surface evidence of low-producing land extending parallel to the East Highline Canal. Extreme care should be exercised in making a stratum survey if this condition is suspected. Drain facilities must be located accurately with respect to the configuration of the subsurface stratum interface.

The occurrence of lenses of sand ranging from 10 square feet to several acres in extent within a large area of quite compact clays is of considerable importance in drainage planning. This condition is most commonly found in the northeastern and north central portion of the Valley. These lenses are difficult to delineate and are often missed in a reconnaissance survey. The soil surveyor should be on the lookout for them in these districts.

The space devoted to a description of the structural characteristics of the clay group is believed justified by the fact that the degree of permeability depends largely upon the presence or absence of these structural features. Without them, the colloidal clay is very resistant to water movement. The presence of the interstices, as described above, may be sufficient to allow enough downward percolation of water to a more pervious stratum.

The sands, loamy sands, and sandy loams have varied structures. Sands are often found with distinct bedding planes and several types of crossbedding. Bedding planes are marked either by paper-thin discontinuous laminae of clay (fig. 5, C), slight changes in grain size, or lines of ferromagnesium minerals (fig. 5). Lath-like arrangement of the sand grains may be the only structural characteristic. This obviously is not visible, but microscopic observation of the grain angularity, together with permeability studies, indicates the presence of this characteristic (fig. 5, D).

The Imperial Valley sands are extremely fine, and the individual grains are angular. The angularity of the sand grains has led to overestimation of the grain sizes and percentage of sand present in the field. The large majority of the sand particles of the southern and central portions of the Valley have maximum diameters of less than 0.25 centimeter. With the exception of sands located along the margin of the Valley, they all may be classed as fine or very fine. Most of the sands are well sorted, with the great majority of particle sizes falling within narrow limits.

Character of stratification

No extensive survey of the Valley has been made by the Imperial Valley drainage investigation, and zoning of the stratum characteristics has been very limited. Survey work has been confined primarily to single farm units scattered widely over the Valley. Prior to construction of the main trunk-drainage system in 1920, a soil investigation was made by the Imperial Irrigation District. Borings were made on east-west profile lines with spacings varying from 660 feet to 5,280 feet, and the design of the system was based largely on the information developed by these studies.

Several deep borings to a maximum depth of 55 feet were made by the Imperial Valley drainage project in cooperation with the City of El Centro. These borings were located just north of the city limits. It was found that a clay-surface stratum was underlain by sands at depths ranging from 13 to 30 feet. At the point where the sands were nearest to the surface, drilling to a total depth of 55 feet did not break through them. A similar sand body much nearer to the ground surface was observed several miles to the north.

The lack of extensive continuous aquifer materials is emphasized here because of its restriction upon large scale-unit drainage undertakings. No consistent pattern of stratum sequence has been observed that leads to a set of rules for the Valley as a whole. Sharp textural breaks are usually the rule, but considerable gradation occurs both vertically and horizontally, particularly in the lighter textured materials. Clay and sand strata have sometimes been found to have fingered horizontal contacts, and isolated slivers or wedges of clay are often found within the sandier sediments. Sand strata having thicknesses of more than 2 feet are usually found to be continuous over areas of more than 50 acres. A continuous sand stratum of unknown thickness underlies the Meloland Experiment Station Farm, and a similar one underlies the Blenkiron property 2 miles east of El Centro.

The Imperial Valley lies within an active fault area. Surficial evidence of recent movement along these faults may be observed. A few striking examples of stratum displacement have been found. Furthermore, it seems apparent that earthquake action has caused considerable extrusion of saturated sandy substrata through the finer textured clays, thus modifying their drainable character.

In summary, the following general rules apply to the carrying on of a strata survey in the Imperial Valley:

(1) Holes should be bored at least 9 feet deep, with occasional deeper borings.

(2) Auger borings should be supplemented by explorations with devices which will bring to the surface undisturbed samples of soil for examination.

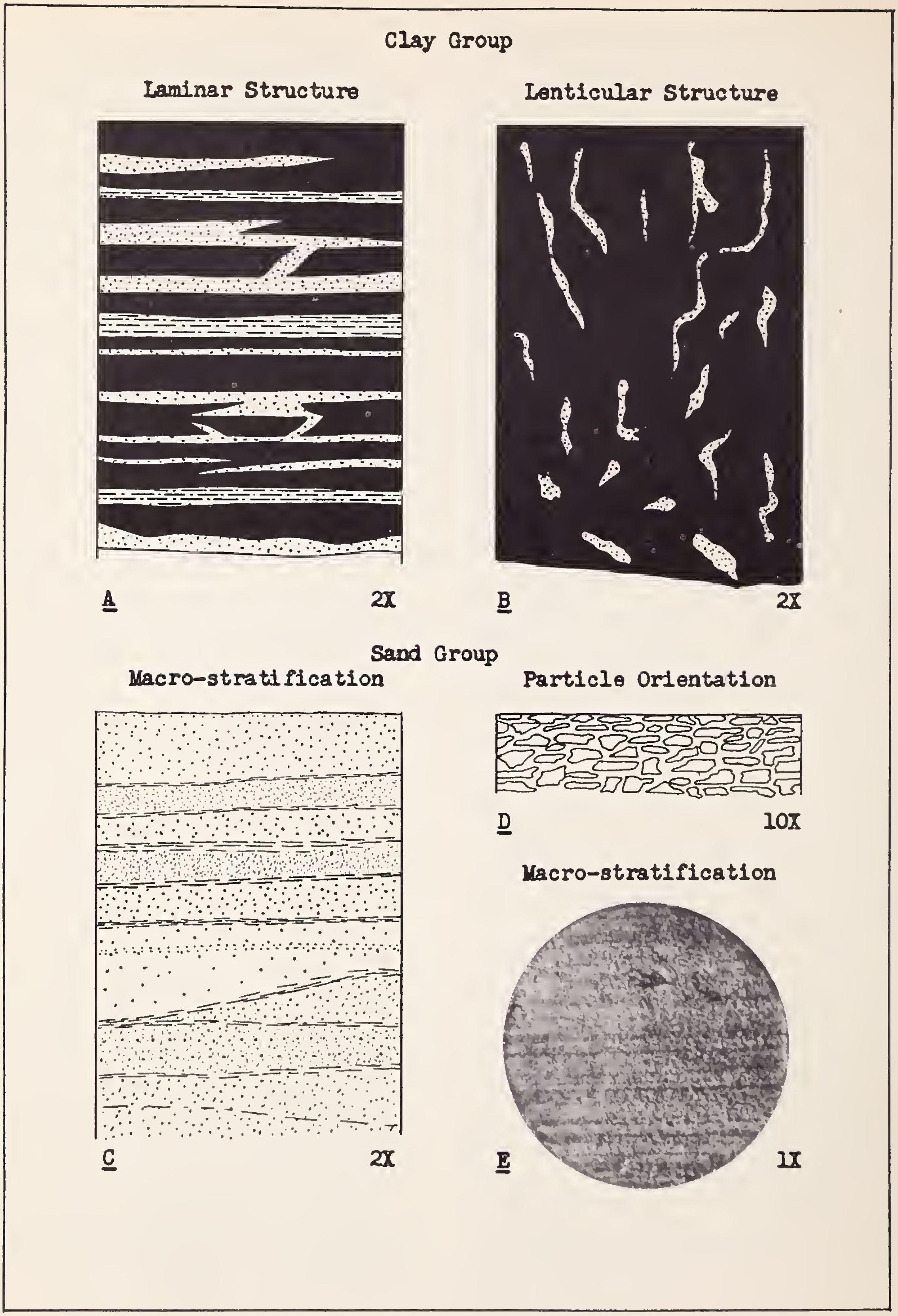


Figure 5.--Structures common to Imperial Valley, Calif., sediments.

(3) Borings should be well organized on a grid, logged in the field, and carefully recorded.

(4) Individual strata should be located, positioned, and classified with significant modifications noted.

Ground-Water Survey

Practically all studies of drainage problems call for a determination of the water-table levels and fluctuations. If the technician is to design a drainage device or recommend a remedial measure intelligently, he must have information on the water-table source and gradient.

In the investigational work being carried on in the Imperial Valley, it was evident that accurate data on the location and movement of the water table were needed. Subsoil-water hydraulics are complicated by the same phenomena that beset soil surveying. Mûltistratification inherent in the soils of the Valley make for a complex problem of locating water source and even water-table elevation. Generally, there are no large shallow water-bearing aquifers under hydrostatic pressure in the Imperial Valley. If there were, they could be located and tapped with relief wells. Therefore, except on the fringes of the Valley and in several localized areas, the water tables causing the drainage problem are probably perched, interconnected, and disconnected water-bearing strata.

To locate and study these water tables, the project developed and used a simple and satisfactory small-diameter observation well, technically termed a piezometer.

Piezometers

The application of the term "piezometer" to devices used in subsoil-water hydraulics is not new. It was used by McLaughlin and Israelsen for such an instrument in 1932 (13). The present instrument was devised by the U. S. Regional Salinity Laboratory and first used in Imperial Valley in 1942. It involves simplifications in the technique of installation and operation which have increased its usefulness. Since that time, piezometers have found application in the solution of many ground-water and drainage problems in the Imperial Valley and elsewhere. Briefly described by Christiansen (1), they have also been mentioned by Israelsen and Reeve, and are further described in detail by Donnan and Christiansen (6). The ground-water piezometer consists of a standard 1/4- or 3/8-inch galvanized iron pipe driven vertically into the ground to a definite level. Before the piezometer is driven, a loose rivet is placed in the lower end to keep out the soil. When the desired depth is reached, a jointed rod is inserted, and the rivet is punched out, leaving an open pipe or well (fig. 6). A small cavity is then flushed out of the lower end of the pipe, using a stirrup pump and plastic tubing. The piezometer thus becomes a very sensitive observation point by hydrostatic pressure. In some soils, the protecting rivet is not needed.

Removal of piezometers

The piezometer pipes may be used many times if care is taken in removing them from the ground. Lengths of pipe up to 8 feet usually can be pulled by hand after being loosened by turning with a pipe wrench. Several adaptations of an ordinary soil-tube jack have been used for removing pipes used in deeper installations. One consists of a set of small grippers that fit around the piezometer and are raised by the jack. A better method involves an A-frame or tripod of 2 x 4-inch material from which is suspended a ratchet hoist. A steel chuck clamp is fastened to the piezometer and attached to the hoist pull chain. When the pipe is removed, it should be cleaned of soil and corrosive scale and straightened. Some pipe has been used as many as 6 times.

Application of piezometers

The principal advantage of piezometers over other devices used for determining ground-water levels lies in their simplicity, ease of installation, accuracy, and low cost. The Imperial Valley investigation project has used them to study flow potential and hydraulic gradient about a tile line. By locating the termination points of the piezometers above, at the sides of, and below the tile line, the hydrostatic pressure causing the water to enter the tile can be charted. It has been found by experiments in the laboratory and field that water travels to a point of release in streamlines (fig. 7).

Schlick (15) recognized the concept of streamline flow of ground water into drainage devices as early as 1918. It was only recently however, that Kirkham, Harding and Wood, Muskat, and others graphically reproduced streamline flow in the laboratory. They have laid the foundation of the application of this concept to drainage design and have worked out some of the principles underlying it.

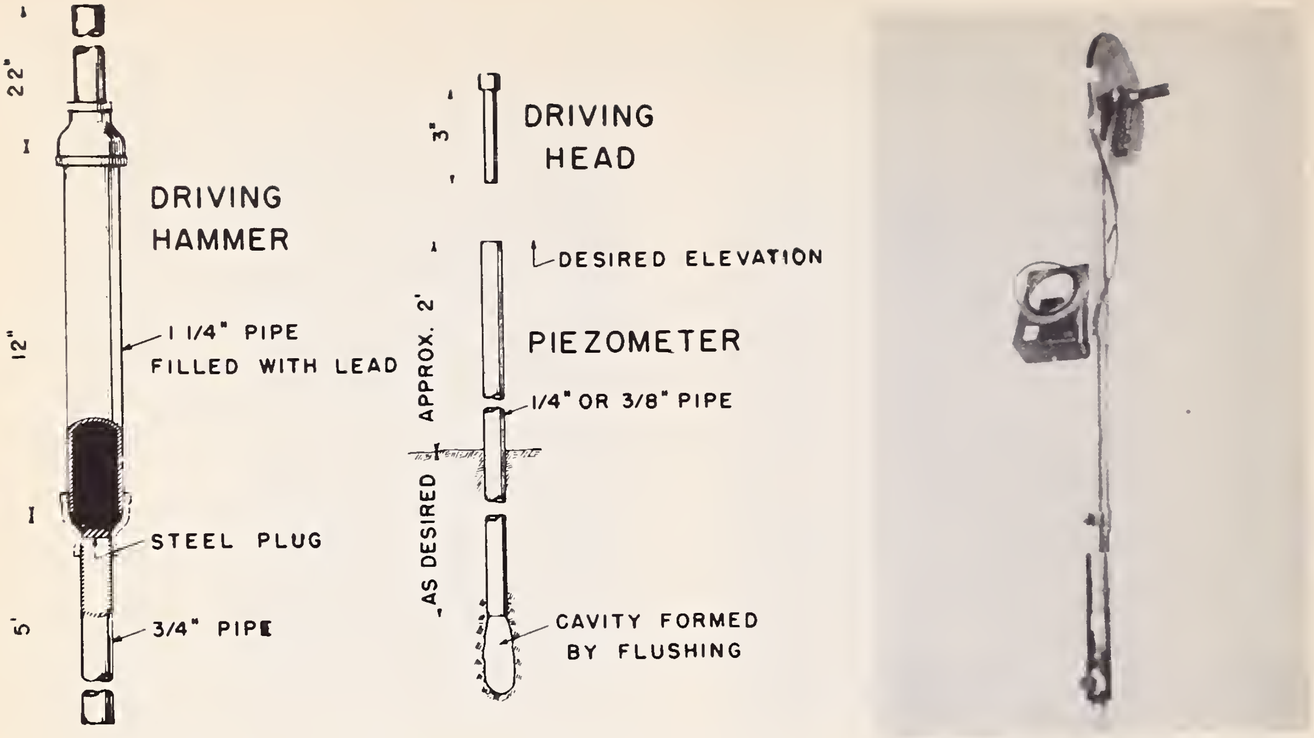
The concept of streamline flow of ground water in a soil profile, whether it be flow toward a drainage device or flow in any direction of release, follows the laws of Laplace's equation. The path of flow to a point of release does not follow a straight vector line but assumes a path of continuity dependent upon the equipotential pressure at any point out from the point of release. Since in a tile line there is a release of hydrostatic pressure above, at the sides of, and below the tile line, it follows that there is a flow at those points convergent to the tile line. Consequently, water originating at the surface of the ground follows a path of flow which curves downward and up into the tile in streamlines (fig. 7).

This concept immediately suggests several companion theories:

(1) That there is a hydrostatic-pressure pattern below a water-table surface.

(2) That the pattern of flow into a drain extends below the drain to a considerable depth.

(3) That the pattern of flow may change with



A- Detail of driving hammer and piezometer. (Drawing from "Ground-water studies in relation to drainage" by J. E. Christiansen.)

B- Electric water level indicator.

1- Weighted tip.
2- Scale.
3- Reel.
4- Milliammeter.
5- Seating sleeve.

Figure 6.--Piezometer well, driving hammer, and water-level device

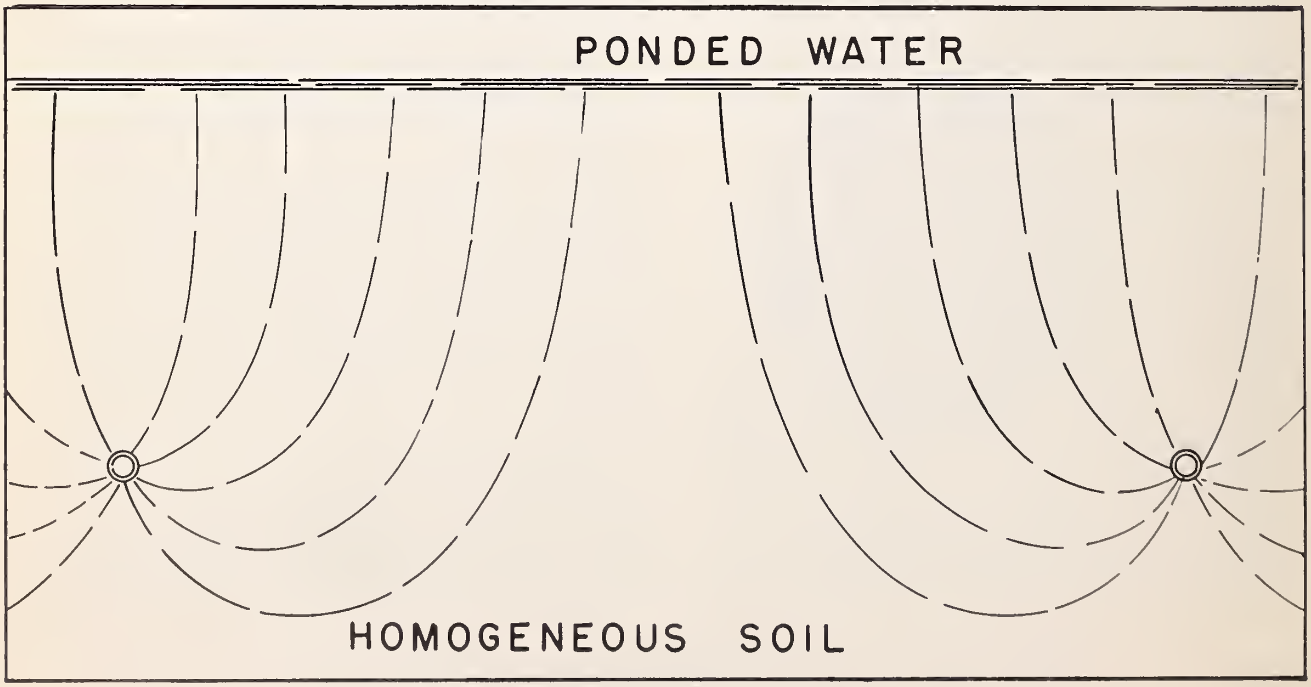


Figure 7.--Streamline flow into drainage tile.

spacing and depth of the drains or stratification of the soil.

Investigations in both the laboratory and field in the Imperial Valley substantiate the experimental results. In experiments on tiled fields, 4 piezometers were put down at each location adjacent to and out from the tile lines. These observation wells terminated at depths of 4 feet, 7 feet, 10 feet, and 14 feet below the surface of the ground. The hydrostatic pressure at the termination points of the wells was determined, and the flow pattern to profiles was charted. The object of placing observation wells in batteries of 4 and at different depths at each location was to obtain enough points of hydrostatic pressure to be able to plot equipotential contour lines. Thus, it could be assumed that any particles of water originating outward from the tile lines would travel toward the point of release (that is, the tile line) at right angles to the lines of equal pressure.

These flow lines in the field studies have always plotted as streamlines, and the interpretation of this phenomenon has thrown new light on the problems facing the drainage engineer. It is possible to trace with ease the source and direction of seepage from canals. The effectiveness of both tile and open drains can be determined. Analysis can be made of the efficiency of sumps and wells, and definite presence or absence of artesian pressure can be determined. The streamline flow concept can be used to locate the best position for an interceptor-tile line or a tile line to dewater low pockets in the substratum barrier. In fact, the project has used the piezometric technique and streamline-flow concept (fig. 8) in all its field work and has made trial or pilot studies on all of these special phases of the problem.

The most general use of the piezometric technique has been in getting overall water-table information in connection with farm-conservation planning and the attendant drainage-design information. The wells are installed after borings are made and the aquifers and barriers are located. The field borings, when plotted in sequence, indicate at what depths the piezometers should be driven. Where the borings indicate that there are several aquifer and aquiclude layers separated by the heavy-clay stratum, both aquifer layers should be tapped with a set of wells. One well taps the upper layer of water-bearing stratum, and the other penetrates through the clay to the lower stratum. Any differential in hydrostatic pressure between the two aquifer layers will be indicated by the well readings.

The axis of the line of piezometers is generally located at right angles to the canal bordering the property or the drain or some topographical feature which is suspected of being an influence on the water table. In some cases, the soil borings reveal subsurface dikes of clay which inhibit the natural flow of the water table laterally, or they reveal deep sand pockets and subsurface clay lenses which dip or cup. The pattern of the wells should cover these stratigraphic features. The farm-conservation planner will find the piezometer a very useful tool in solving the problems of drainage on an individual farm.

Coefficient of Permeability

A quantitative determination of the coefficient of permeability (P) of the strata underlying the soil surface in the Imperial Valley is essential in the development of sound techniques of land drainage. Without quantitative determinations, estimates of permeability are not only difficult to make but often very misleading. Coefficient of permeability has been defined as "the rate of flow of water through a unit cross-sectional area with a unit head." It must be assumed that all large, and nearly all smaller pores, are filled with water and are contributing to the transmission of water. Coefficient of permeability should not be confused with rate of infiltration.

From Darcy's law, the coefficient of permeability may be expressed by the formula

$$P = \frac{Q}{IA}$$

where P = coefficient of permeability,
Q = quantity of water discharged per unit of time,
I = hydraulic gradient, and
A = cross-sectional area of stratum (or specimen) through which the water moves.

The coefficient of permeability is a quantitative value. For field work, the coefficient of permeability is expressed in gallons per square foot per day (gals./ft.^{2}/day) while in the laboratory it is more convenient to use cubic centimeters per square centimeter per hour (cc./cm.^{2}/hr.). The laboratory values may be converted to field units or the reverse by multiplying or dividing by 5.27.

A group of symbols has been set up to indicate the various types and sources of information concerning permeability that were used in the Imperial Valley. These are outlined as follows:

Permeability terms

P = Coefficient of permeability in gal./ft.^{2}/day.
K = Coefficient of permeability based on comparison with the mechanical analysis of other samples or the curve.
K_c = Coefficient of permeability based on comparison or curve but corrected for field horizontal permeability in cc./cm.^{2}/hr.
K_p = Coefficient of permeability based on actual laboratory measurement of prepared samples in cc./cm.^{2}/hr.
K_v = Coefficient of permeability based on actual laboratory measurement of an undisturbed specimen taken normal to the apparent bedding plane.
K_h = Coefficient of permeability based on

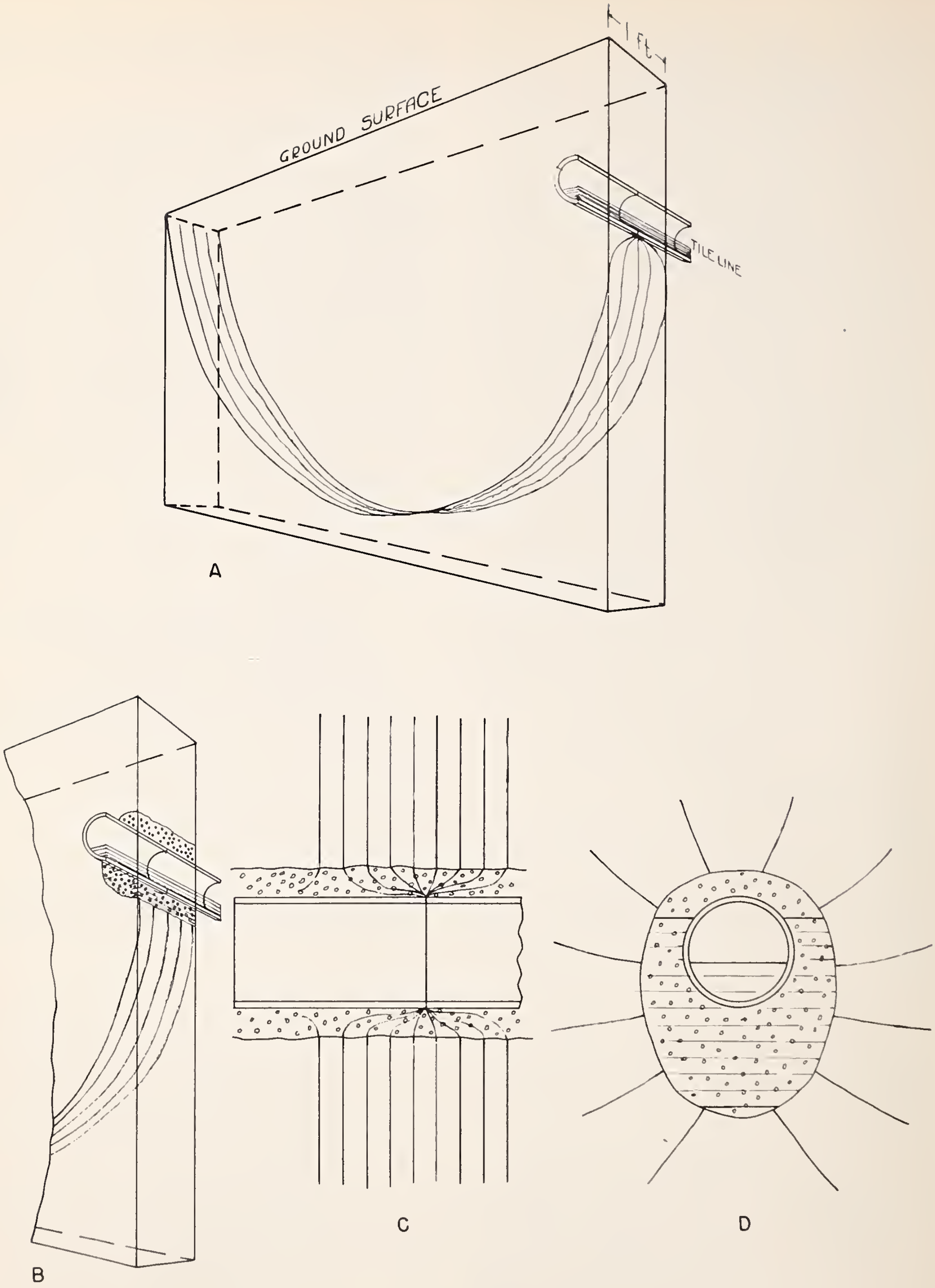


Figure 8.--Diagram of streamline flow into tile line with and without gravel envelope.

actual laboratory measurement of an undisturbed specimen parallel to the apparent bedding plane.

Procedure

There are three methods of determining quantitatively the coefficient of permeability of any single stratum or group of strata. These methods are outlined as follows:

1. Field measurement.
   A direct measurement utilizing a small well and measuring the discharge from the well and the equilibrium drawdown curve to it.
2. Laboratory measurement utilizing the permeameter.
   a. Undisturbed specimens taken in the field.
   b. Disturbed or prepared specimens. These are samples taken in a disturbed condition from the field site and prepared in the permeameter under standard procedures.
3. Indirect measurement of permeability.
   a. Mechanical analysis as an index of permeability. This is an empirical method based on considerable data accumulated during the Imperial Valley drainage investigation.

The first technique is perhaps the most accurate, but also the most time-consuming and subject to complications of varying field conditions. The second method is quite accurate when undisturbed samples are used. This method also is time-consuming and exacting. The indirect method is not precise but it is rapid and reasonably simple. A greater degree of accuracy is derived when these estimates are supplemented with undisturbed sample-laboratory measurements.

Field measurement

Several formulas, based on the flow of water into discharging wells, can be used either directly or indirectly for the determination of permeability. A basic assumption of these formulas is that the cone of the depression around the discharging well has reached equilibrium.

A simple development of one of these formulas has been used as follows (fig. 9): Applying the Darcy law to conditions surrounding a discharging well, $Q = P\ I\ A$, where $I = dy/dx$, and $A = 2\pi xy$. Substituting in the formula, then

$$Q = P \frac{dy}{dx}\ 2\pi xy$$

$$\frac{Q}{2\pi P} \times dx = y\ dy$$

Integrating between the limits,

$$x = R_1\ \&\ R_2$$

$$y = h_1\ \&\ h_2$$

$$\int \frac{Q}{2\pi p} \log_e R_2 - \log_e R_1 = \int \frac{h_2{}^2 - h_1{}^2}{2}$$

or

$$P = \frac{Q \log_e \dfrac{R_2}{R_1}}{\pi\left(h_2{}^2 - h_1{}^2\right)}$$

Factoring,

$$\left(h_2{}^2 - h_1{}^2\right)$$

$$(h_2 - h_1)\ (h_2 + h_1)$$

but,

$$(h_2 - h_1) = (S_1 - S_2),$$

therefore,

$$P = \frac{Q \log_e \dfrac{R_2}{R_1}}{\pi(h_2 + h_1)\ (S_1 - S_2)}$$

This is the formula used to secure permeability coefficients in the field. To secure the field data, a stratum survey is made of the proposed well site. A small gravel-envelope well is then put down, tapping the aquifer. After laying out a system of piezometers about the well, pumping begins and continues until an equilibrium curve is secured on the drawdown around the well. At this point, a determination of all the factors needed to secure the permeability coefficient can be made. The quantity of water (Q) is secured by measuring the discharge from the well. Hydraulic gradient (I) is determined by the position of the drawdown curve in the piezometers. Area (A) has been determined by borings. Then solve for coefficient of permeability (P) in the formula.

Laboratory measurements by V. S. Aronovici

In the laboratory, soil permeability is measured using the discharging permeameter. This equipment is so designed that the discharge and loss of head of water as it passes through the specimen can be measured. The head-of-water application is maintained at a constant level. Below is given the basic formula for the permeameter:

Discharging permeameter. --For discharging permeameter,

$$K_p = \frac{Q}{IA}$$

when K_p = coefficient of permeability of prepared specimen
Q = discharge in unit of time
A = cross-sectional area of the soil column
I = hydraulic gradient
L = length of soil column
$h_1 - h_2$ = head loss between two points in the soil column
Ct = temperature correction
V = volume discharge in cc
T = time

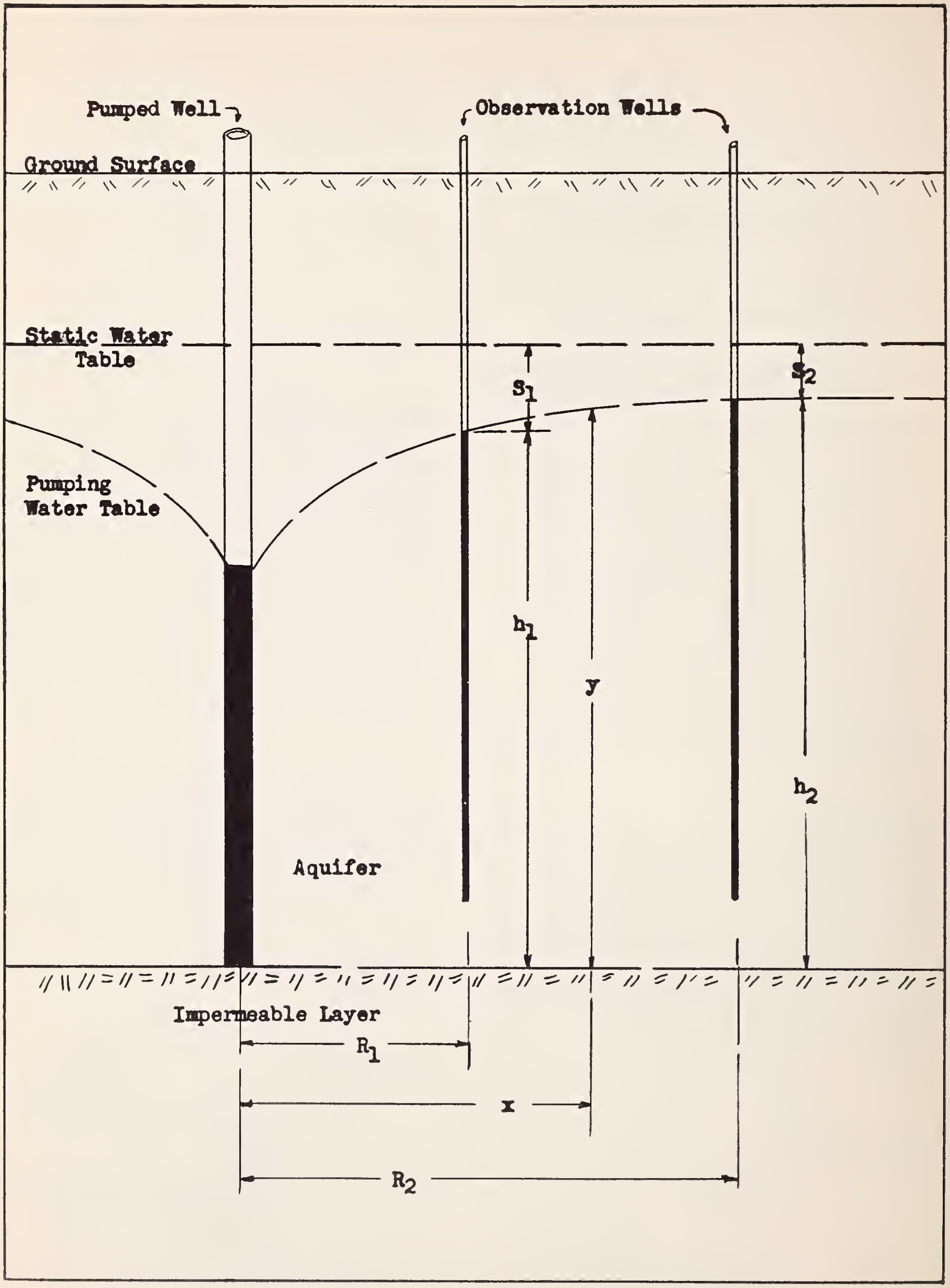


Figure 9.--Diagram of factors involved in calculating soil permeability coefficient from field experiment.

Substituting the values,

$$Q = \frac{V}{T} \quad \text{and} \quad I = \frac{h_1 - h_2}{L}$$

then

$$K_p = \frac{VLCt}{T\ A\ (h_1 - h_2)}$$

Units for most laboratory work are expressed in cubic centimeters squared and hours.

The temperature-correction factor is an essential part of the formula. It is based on the water viscosity in centipoises where 20° C. is 1.0050 or, for practical purposes, unity. For example, when the temperature is 25° C., then the observed value is raised by multiplying by 1.1404 (table 6).

TABLE 6.--Temperature correction for coefficient of permeability measurements

Temperature, in degrees		Viscosity, centipoises	Temperature, in degrees		Viscosity, centipoises
Cent.	Fahr.		Cent.	Fahr.	
15	59.0	1.1404	25	77.0	0.8937
16	60.8	1.1111	26	78.8	.8737
17	62.6	1.0828	27	80.6	.8545
18	64.4	1.0559	28	82.4	.8560
19	66.2	1.0299	29	84.2	.8180
20	68.0	1.0050	30	86.0	.8007
20.20	68.36	1.0000	31	87.8	.7840
21	69.8	.9810	32	89.6	.7679
22	71.6	.9579	33	91.4	.7523
23	73.4	.9358	34	93.2	.7371
24	75.2	.9142	35	95.0	.7225

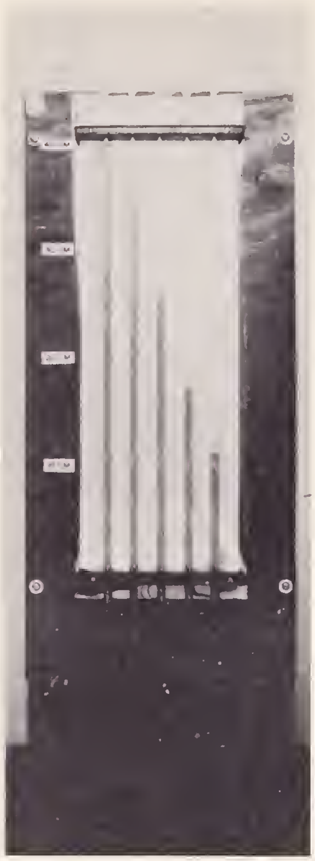
Packed sample permeameter.--This unit is constructed of brass tubing approximately 5 centimeters in diameter, with a wall thickness of 0.12 centimeter. The tube's length is 30 centimeters overall. The top of the tube is open while the bottom is capped by a perforated plate with an inner ring upon which a screen rests. An inlet tube is connected to the base below the screen. A manometer-takeoff tube is attached to the wall of the permeameter 4 centimeters above the screen. Three others are placed at 6-centimeter intervals above and are rotated around the tube at 22.5-degree angles. Two centimeters below the top of the tube are 2 outlet tubes, one for an outlet manometer and the second for the outflow.

Before the soil sample is placed in the permeameter tube, a filter paper, cut to fit exactly inside the tube, is placed over the screen at the base. Each of the manometer-takeoff tubes, 5 centimeters in length, is carefully packed with glass wool. This step is most important, since too much packing will prevent free flow of the water from the permeameter into the manometer tube, thus giving false readings.

The permeameter is then mounted on a simple rack made of a woodblock 3 inches thick, 12 inches long, and 8 inches wide. Two uprights are secured to the block at the ends of an 8-inch side to support a plywood panel 22 inches high. Milliammeter-grid paper is pasted to the panel so that the manometers may be read easily. The 5 manometers are 24 inches in length and of 8-millimeter outside diameter, and are attached to the wood panel with wooden cleats. A right-angle bend at the lower end of the tubes passes them through openings in the panel to the back. Short lengths of rubber tubing connect the manometer takeoff tubes with the glass manometers. A 1/4-inch iron pipe is inserted into the back of the woodblock and extends above it about 15 inches so as to be useful as a stand on which the permeameters are attached by means of large laboratory clamps (fig. 10).

An outlet tube is then attached to the permeameter. This unit is made of a short rubber tube which connects the permeameter with a T-joint, the crossbar being in the vertical position. The lower end of the bar is inserted into a 10-cubic centimeter burette. The upper end is left open to prevent siphoning of the water from the permeameter. It is occasionally necessary to place a very small quantity of glass wool on the outlet end of the T-joint to break the surface tension and provide even flow into the burette. A stopwatch records the time required for a specific quantity of water to accumulate in the burette. Five cubic centimeters is the unit most frequently used.

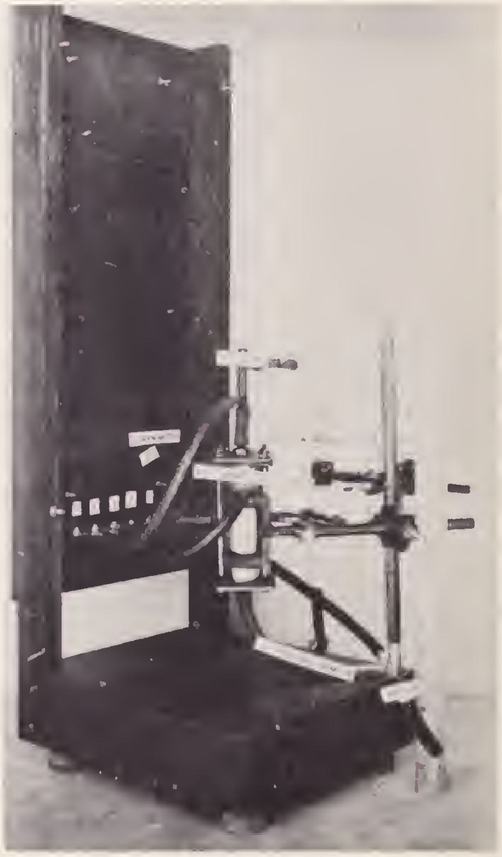
Observations are taken more frequently during the early portion of the permeability run than later for the purpose of obtaining the characteristics of the fluctuation during that period. Twice daily is satisfactory. As the fluctuations diminish, once a day is sufficient. A convenient method of setting up record and calculation sheets is as follows:



A

A- Front view of permeameter rack.

B- Rear view of permeameter rack showing permeameter intake, outlet assembly and manometer attachments.



B

Figure 10.--Permeameter rack: A, front view; B, rear view, showing permeameter intake, outlet assembly, and manometer attachments.

Sample No. 122 Type Perm. Inplace Rack No. A Tube No. 4 Wt. 290 Vol. 187 Vol. Wt. 1.55

Readings

Date	Hour	Period hrs.	Total hrs.	Manometer readings, cm.					cc.	Time	cc./hr.	Temp. C°	t cor.
				h_1	h_2	h_3	h_4	h_5					
8/12	11:00	22.00	22.00	39.50	25.00	20.70	16.30	10.65	5	2'58"	116.2	22.0	0.957

Permeability calculations

Date	Total hrs.	$h_2 - h_3$	$h_3 - h_4$	$h_2 - h_4$	Q	t cor.	$P_2 - P_3$	$P_3 - P_4$	$P_2 - P_4$
8/12	11:00	4.30	4.40	8.70	116.2	0.957	4.17	4.08	4.10

The most convenient method of recording time of day is by the decimal system and using a 24-hour day, rather than a.m. and p.m. This system greatly simplifies the adding of cumulative hours in the total column. Calculations, with the data set up as given above, can be made with a slide rule rapidly and with sufficient accuracy.

Inplace (undisturbed) permeameter.--The only difference in the operation of the inplace permeameter and the packed sample permeameters lies in the technique of taking the sample and setting up the unit for installation on the permeameter rack. The term "undisturbed" or "inplace" designates a sample taken from a field site with minimum of disturbances of structure.

The permeameter tube is so designed that, when samples are to be taken, both end pieces can be removed. Sampling is facilitated by a specially designed unit consisting of 2 ship augers 1 inch in diameter connected to 18-inch shafts with T-shaped handles. The most satisfactory samples are taken when the sediment is quite moist but not wet. Saturated sands, especially, tend to flow out of the permeameter before they are moved to the laboratory or the structure is destroyed by jar in transit. Driving of the tubes into the sample by pounding should always be avoided.

After the permeameter tube has been driven full depth into the sample, the soil is cut away and a spatula pushed underneath the tube so that it may be lifted free. The ends are then shaved down with a knife, flush with the cylinder. These ends are then carefully capped with wax paper, and the unit is packed in cloth so that there will be little or no jarring in transit to the laboratory.

In the laboratory, the wax-paper caps are removed and exactly 0.5 centimeter is cut from each end of the tube by means of a special rotating cutting tool. The tool has a collar which fits down over the permeameter tube so that the depth of cut may be exact. Into each end are placed snugly fitting filter papers and screen. Then a fluted plate, slightly less than 0.5 centimeter thick and with an opening into which a threaded tube fits, is placed on each end. A square of rubber gasket material with a hole in the center for the threaded tube is placed over the plate. Brass plates are then placed over the gasket at either end of the tube and held securely in place by 4 long bolts soldered at one end and threaded at the other. The unit is tightened with nuts at the threaded end, and large nuts are threaded on the brass intake and outlet tubes. A very thin coating of stopcock grease smeared over the gasket at the point of contact with the tube prevents leakage. The manometer plugs are removed and the takeoff tubes are replaced. All calculations and methods of measurement are identical with those described for the first type of permeameter.

Water supply.--Regardless of the type of permeameter, the selection of the water for use is very important. The original degree of flocculation must be maintained. The use of distilled water in the Imperial Valley, for example, would very quickly cause all of the dissolved salts to be leached out. The soil particles would deflocculate and greatly reduce the coefficient of permeability. Colorado River water, on the other hand, contains about the same group of salts as the average ground water although in much lower concentrations. No change in degree of flocculation has been observed from the use of this water.

Making permeameter tests.--Permeability observations are made daily during the permeameter run. Interesting observations can be made from plotting the permeability coefficients against time. Usually the rates pass through 3 stages. During the first period, varying in length from 100 to 200 hours, they increase. The second period, from 200 to 600 hours, shows little change. The average over this period, when permeability-coefficient values remain nearly constant, is used for the final value. The third period, characterized by a reduction in rate, usually shows within a total elapsed time of from 300 to 500 hours. The texture of the sample has a strong effect upon the length and amplitude of these periods, which may further be influenced by the quantity and quality of water flowing through the sample. Samples taken in place occasionally show less fluctuation in the early stages of the run, especially if they are nearly saturated when taken.

The most plausible explanation of this phenomenon is that, during the early stages of the run, air trapped in the soil-pore space is gradually dissolved, increasing available porosity; thus the rate of permeability increases.

Materials of very low permeability do not show this cycle strongly; there is a very gradual rate of increase for a much longer period of time than in the coarser materials. If the run is long enough, the same type of curve may be observed. Much difficulty has been encountered in obtaining uniform rates with materials of high permeability.

Evaluation of procedure

The degree of reliability of permeability measurements as they compare with actual field values is of primary importance. The ability to duplicate experimental results is a further essential to the establishment of a sound technique. These problems were considered carefully.

Comparison of laboratory and field measurements.--Several comparisons were first made of the laboratory measurements of permeability (K_h, K_v) with actual field measurements, using the Wenzel (19) technique. As an example, the average coefficient of permeability as measured in the field was 6.9 cc./cm.^{2}/hr. Other tests indicated nearly the same degree of accuracy, but laboratory measurements consistently appear to be slightly the lower.

Comparisons were then made of duplicate runs of both prepared and undisturbed specimens. Average deviation from any duplicate group was 8 percent. This error is based upon the limits of the maximum and minimum values of any single sample. Since the permeability most commonly encountered in the Imperial Valley is considered to range from 0.5 to 50 cc./cm.^{2}/hr., the overall error is reduced considerably. When this total range is expanded to a possible 0.005 to 1,000 cc./cm.^{2}/hr., the error is negligible.

Comparison of results (horizontal, vertical, and prepared samples).--In nearly all types of drainage, the greatest distances traveled by water are usually horizontal. Therefore, the horizontal permeability value must be used in computing permeability for tile or drain-ditch facilities. Comparison of the ratios between the vertical, horizontal, and prepared samples (table 7) taken at one station with those of similar series at other stations shows considerable variation. Specimens taken parallel to the bedding plane usually have higher coefficients of permeability than the vertical samples. Prepared samples most commonly have a permeability similar to, or somewhat lower than, the horizontal specimen.

TABLE 7.--Coefficient-of-permeability relationship of undisturbed to prepared sample for a few specimens

Sample No.	Coefficient of permeability in cc./cm.^{2}/hr.			Relationship (ratio)			Correction factor
	Vert.	Horiz.	Prepared	Vert.	Horiz.	Prepared	Horiz. Prepared
123............	9.4	11.5	8.1	1.0	1.2	0.9	1.4
125............	8.9	14.2	9.2	1.0	1.6	1.0	1.5
122............	8.4	14.0	3.5	1.0	1.7	.4	4.0
329............	21.3	26.2	14.0	1.0	1.2	.7	1.9
149............	8.1	11.5	8.5	1.0	1.4	1.1	1.4
311............	10.7	31.6	4.3	1.0	3.0	.4	7.3
313............	9.1	12.8	5.8	1.0	1.4	.6	2.2
46E............	4.8	10.9	4.9	1.0	2.3	1.0	2.2
312............	9.0	9.3	2.2	1.0	1.0	.4	4.2
339............	5.1	6.4	1.7	1.0	1.2	.3	3.8
338............	3.3	4.0	.7	1.0	1.2	.2	5.7
213A...........	3.9	6.7	1.0	1.0	1.7	.3	6.7
213B...........	1.0	1.1	.4	1.0	1.0	.4	2.8
212A...........	4.0	4.4	.4	1.0	1.1	.1	11.0
212B...........	3.0	5.6	.8	1.0	1.9	.3	7.0

Needs for shortcuts.--It is obvious, from the foregoing discussions dealing with the methods of making the stratum survey and measurement of permeability, that shortcuts are in order for evaluating the coefficient of permeability of the aquifer. Extensive planning of drainage facilities in agricultural areas such as the Imperial Valley requires numerous samplings in order to derive a representative permeability value. To be practical, some more rapid technique of estimating permeability is necessary, even though it may involve sacrifice of some degree of accuracy.

Attempts were made to develop a relationship between some simple characteristics of a sediment and the coefficient of permeability. They include the plastic limit, moisture equivalent, water-holding capacity of the sediment at various tensions, and the character of the particle-size distribution curve. All of these methods probably have merit when applied to special conditions. They were considered for application to Imperial Valley conditions. Either they did not apply to local problems, or the techniques involved required complicated equipment or special training on the part of the technician.

Correlation of the percentage of silt-plus-clay with the coefficient of permeability of a prepared specimen was then attempted. The techniques involved required very little equipment and limited experience on the part of the technician.

The mechanical analysis as an index of permeability

A soil or sediment has the ability to transmit water because of the interconnecting pores. Pore-size distribution is in part a product of grain-size distribution, or texture. Pore size, rather than total porosity, determines the coefficient of permeability. However, sediments containing considerable clay commonly possess structural features which affect pore size more strongly than the grain-size distribution. Methods of estimating permeability by using the mechanical analysis alone must, therefore, be confined to sediments having a low clay content. Further, the mechanical analysis should not be used as an index of water movement which does not comply strictly to the fundamental Darcy law of flow of liquids through porous media.

These limitations do not become significant for estimating the coefficient of permeability of the aquifer materials. Such a correlation does not account for the fact that structural characteristics of the sediment cause permeability values to be greatest parallel to the bedding plane.

As a result of conducting a large number of mechanical analyses and prepared sample coefficient-of-permeability measurements, a definite correlation was derived between the total silt-plus-clay percent (grain particles smaller than 0.05 mm.) and the coefficient of permeability. Correlation appeared to be most consistent in the permeability range between 1.0 and 30 cc./cm^2/hr., but with good correlation extending from 0.3 to 70.0 cc./cm^2/hr. (fig. 11, A, B). Much above or below these limits, correlation became less definite. The curve drawn in figure 11, A, B, was statistically established by the analysis of the points illustrated. A highly significant correlation was established ($r = 0.85$ when $n = 83$).

Procedure in deriving estimates of permeability used by V. S. Aronovici

The mechanical analysis.--The specimen is brought into the laboratory, given a laboratory number, and ovendried at 105° C. It is then placed upon a wooden board and the lumps are broken by a wooden roller. The entire sample is then split carefully by means of an oilcloth sheet or standard sample splitter to 50 or 100 grams. If the sample contains more than 70 percent sand, 100 grams should be separated out. The sample is then placed in a soil dispersion cup with approximately 1/2 liter of distilled water and stirred for 10 minutes. Five cubic centimeters of sodium silicate solution, having a specific gravity of 37 (Bouyoucos hydrometer) at 18.9° C., are added. The mixture is then removed from the dispersion cup and placed in a 1-liter cylinder and allowed to stand 24 hours. Should the upper portion become clear, or nearly so, indicating that all fines have settled, the clear water should be decanted off, the sample again placed in the dispersion cup, and the process repeated. Usually, one leaching of this kind will be sufficient to remove all salts from the solution. Not until these salts are removed will complete dispersion be obtained.

When complete dispersion has been assured, a hydrometer-mechanical analysis may be undertaken. The cylinder is placed in a uniform-temperature bath. A stirring rod with a flat circular head approximately 1/2 inch smaller in diameter than the cylinder is forced rapidly up and down in the cylinder for 20 strokes. At the last upward stroke, the stirrer is quickly removed and a stopwatch started. At the end of 40 seconds, the first reading is taken with the Bouyoucos hydrometer. The second reading is taken at the end of 1 hour, and a third reading is taken at 2 hours. Temperature readings are taken immediately after the hydrometer reading. The cylinder is allowed to remain standing, but may be removed from the uniform temperature bath at the end of 2 hours. At the end of 24 hours, the cylinder should be inspected to check for good dispersion. Hydrometer observations taken at 5, 10, and 30 minutes are often helpful in securing a picture of the silt-size distribution. However, this is not an essential step.

Calculation of the total sand, silt, clay, and colloidal clay is made as follows:

$$\text{Total percent sand} = 100 - \frac{(\text{Corrected hydrometer reading at 40 sec.} \times 100)}{(\text{Absolute dry weight of soil used})}$$

$$\text{Total percent clay } (0.005 \text{ to } 0.002) = \frac{(\text{Corrected hydrometer reading at 1 hr.} \times 100)}{(\text{Absolute dry weight of soil used})}$$

$$\text{Total percent colloidal clay } (-0.002) = \frac{(\text{Corrected hydrometer reading at 2 hrs.} \times 100)}{(\text{Absolute dry weight of solid used})}$$

$$\text{Total percent silt} = 100 - (\text{total clay} + \text{total sand})$$

Estimating the coefficient of permeability.--Upon completion of the mechanical analysis,

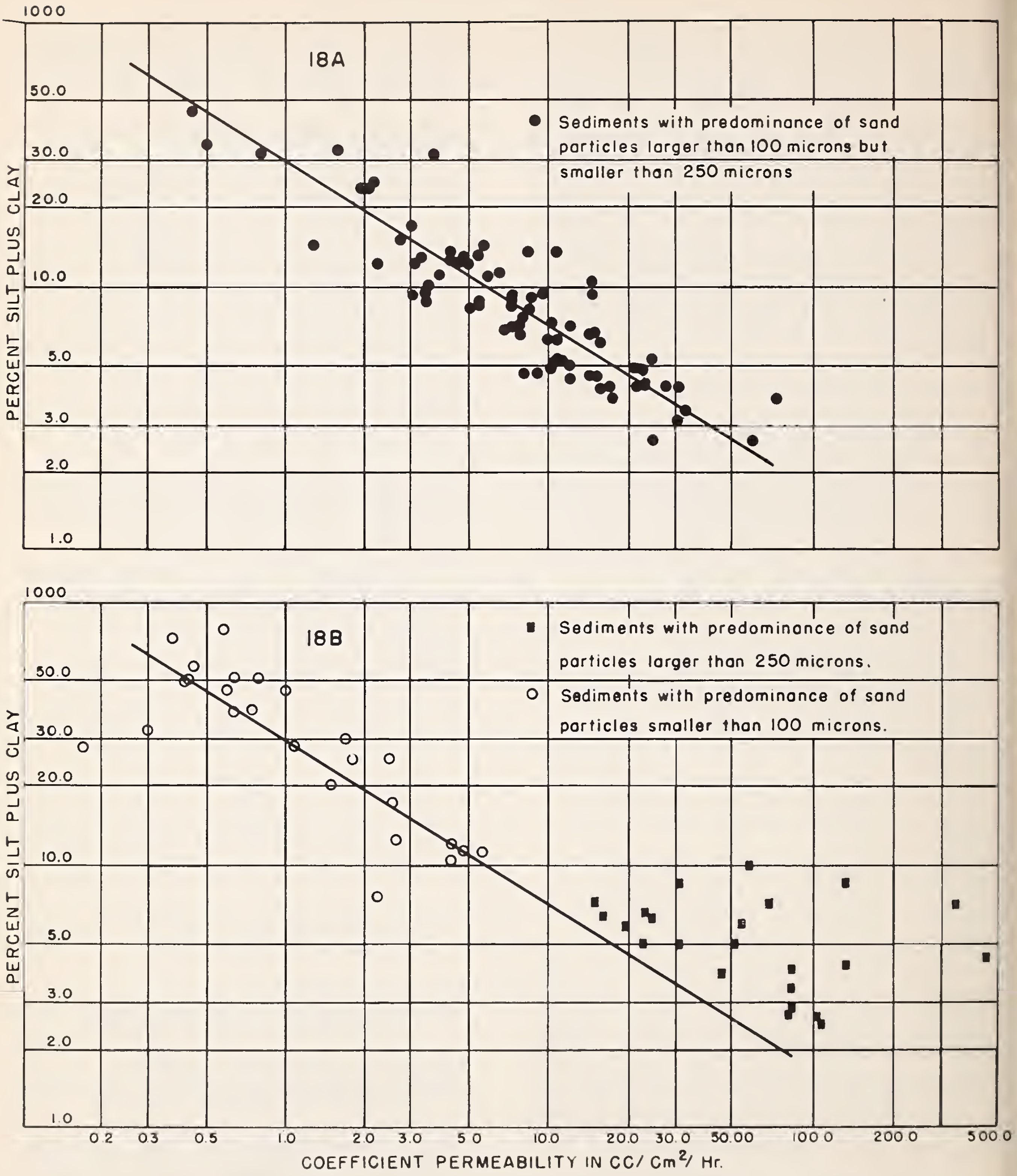


Figure 11.--Ratio between silt-plus-clay content and coefficient of permeability.

the results should be classified as to which of the groups the samples belong. This classification is based upon the predominance of sand grains. A glance at the results of the mechanical analysis will indicate whether the proportion of sand, fine sand, or very fine sand is greatest.

One of two methods is then utilized for estimating the permeability, as indicated in figure 11. The first is by the use of the correlative curve of silt-plus-clay with the coefficient of permeability. This may be used within the silt-plus-clay limits from 2 percent to 68 percent when fine sand is dominant. When the very fine sand is dominant, the silt-plus-clay limits are between 10 percent and 68 percent silt-plus-clay. Sediments predominantly sand, and the sand predominantly very fine sand with more than 68 percent silt-plus-clay, require the second method. This is a comparison of the mechanical analysis with previously measured specimens. For this purpose, a series of cards may be filed on the basis of silt-plus-clay content. These cards contain the mechanical analysis, coefficient of permeability, method of measurement, and laboratory number of sample run.

In all cases, the permeability estimate by the correlative curve indicates the prepared sample coefficient of permeability, and in many cases the reference cards refer to prepared samples. Therefore, a correction factor to establish the horizontal coefficient of permeability value must be applied, as previously described.

Quantity of Water To Be Drained

Irrigation and drainage problems of agricultural lands are inseparable. In Imperial Valley more than 95 percent of all water entering the soil is derived from irrigation. A high water table and consequent potential drainage problem are caused directly or indirectly by seepage or excessive application of water to the land. The presence of dissolved salts in the irrigation water further associates drainage with irrigation. Israelsen (8) has stated, "If it were possible to maintain a moisture distribution in irrigated soils such that moisture movement would be continuously downward, there would be relatively little trouble from alkali on irrigated farms." Thus it is seen that some excess water should be used for irrigation in order to maintain a salt balance in the soil. This water must eventually be drained away from the area where it is applied.

Excess irrigation water

Lysimeter studies by the Bureau of Plant Industry Regional Salinity Laboratory, Riverside, Calif., using alfalfa, have indicated that about 10 percent of the water applied to the soil appears as leachate to maintain a salt balance. Until further investigations indicate a better value, it is believed that 10 percent excess of water is a practical value to apply to the Imperial Valley conditions.

An excess of water is usually caused by: (1) Intermittent leaching (ponding), and (2) excessive irrigation application. Intermittent leaching is a planned program and is undertaken only when the soil solution salt concentration is sufficiently high to reduce productivity materially. To control excess water application requires a measure of irrigation efficiencies, moisture levels, and evapotranspiration. All these factors are difficult to control and nearly impossible for the farmer to measure. However, it appears that leaching by the application of excess irrigation water has a distinct advantage over leaching by ponding. Prolonged ponding of a soil appears to cause a breakdown in soil structure and excessive loss of plant food, and it imposes a heavy tax upon the drainage facility at any one period.

Certain varieties of rice have been utilized in an attempt to coordinate heavy leaching with crop production. With heavy application of water, the salts are leached downward by water percolation, thus lowering the salinity of the surface zone. Subsequent crops of barley have been good, but there has been no conclusive evidence that such improvement is lasting where there is no free outflow of the leachate.

It has been observed that excessive use of irrigation water will, in many cases, directly affect adjoining properties, but no evidence exists that water-table flow is continuous or extensive. This is in part due to the discontinuous stratification.

Water requirements[18]

Water requirements of plants are measured on the basis of the seasonal quantity of water removed from the soil by evapotranspiration. Irrigation requirements vary with crop, soil, and climatic environment. Accurate measurement of the water requirements of alfalfa, for example, are not necessarily the same in one locality as in another.

In order to obtain a reliable estimate of the consumptive use of water, it is first necessary to conduct a series of field observations. A plot was set up on the Dorman Farms. The details of this study are set out in the Progress Report for 1945.[19] Owing to the presence of a water table, which fluctuated between 3.5 and 5 feet, the problem of measuring the rate of evapotranspiration was considerably more complex than in similar investigations when there was no water table. Accurate measurement had to be made of the water applied to the land by irrigation, seepage in and out of the field, and the rate at which the soil moisture was removed from the soil profile by evapotranspiration. Alfalfa-yield records were kept for comparison with average conditions (table 8).

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[18] After report by V. S. Aronovici. See footnote 6 p. 2.

[19] Fox, W. W., Aronovici, V. S., and Donnan, W. W. Imperial Valley Drainage Investigation, Progress Report, 1944-45. October 1945. [Typewritten.]

TABLE 8.--Measured and computed monthly consumptive use of water by alfalfa, Dorman Farms, 1944-45, Imperial Valley, Calif.

Month	Consumptive use of water		Month	Consumptive use of water
	Measured	Computed[1]		Computed[1]
	Inches	*Inches*		*Inches*
November..................	2.52	2.68	July....................	7.71
December..................	3.17	1.99	August..................	7.27
January...................	1.84	1.95	September...............	5.73
February..................	2.42	2.01	October.................	4.15
March.....................	2.19	3.25		
April.....................	4.41	4.33		
May.......................	6.24	6.08		
June......................	5.03	7.03		
Total................	27.82	29.32		24.86
Total annual computed consumptive use of water				54.18

---

[1] Based on Blaney consumptive-use formula.

TABLE 9.--Farm duty of water of representative crops in Imperial Valley, Calif., based on headgate records of the Imperial Irrigation District.

Period	Farm duty of water in acre-inches per acre[1]						
	Alfalfa	Barley	Flax	Milo-maize	Carrots	Lettuce	Cantaloupes
1942							
July..........................	--	--	--	--	2.9	2.5	--
August........................	--	--	0.8	--	1.9	3.8	0.5
September.....................	--	--	3.7	--	3.7	3.8	3.4
October.......................	5.4	0.4	3.4	--	9.5	7.2	.5
November......................	3.6	1.3	2.6	--	4.8	4.8	4.3
December......................	.6	2.6	1.4	--	2.9	2.6	2.2
1943							
January.......................	2.5	3.7	2.6	--	2.8	3.4	2.4
February......................	2.6	3.6	3.5	--	2.3	1.2	1.9
March.........................	4.7	5.8	5.3	--	2.9	--	4.3
April.........................	7.1	1.7	2.4	--	2.4	--	4.6
May...........................	8.5	--	--	2.6	1.2	--	8.7
June..........................	8.4	--	--	6.6	--	--	4.8
July..........................	8.4	--	--	6.5	--	--	--
August........................	2.6	--	--	8.2	--	--	--
September.....................	2.2	--	--	4.2	--	--	--
October.......................	--	--	--	.5	--	--	--
November......................	--	--	--	--	--	--	--
December......................	--	--	--	--	--	--	--
Total.........................	56.6	19.1	25.7	28.6	37.3	29.3	37.6

---

[1] These figures are based on headgate records of the Imperial Irrigation District and show the trend of water use in Imperial Valley. The headgates usually deliver upward of 10 percent more water than is indicated by the gate tables.

The computed consumptive use is based upon the percent daytime hours and mean monthly temperatures.[20] It is apparent that these measured and computed values are close enough to each other to justify expansion of the data through the entire irrigation season. These data indicate that, under average conditions, the annual consumptive use by alfalfa for a 12-month period in the Imperial Valley might be 54.18 inches. However, it is the common practice to allow the alfalfa plants to become dormant between July 15 and September 15. Thus, average seasonal consumptive use should not be greatly in excess of 48 inches for the 10-month period September 15 to July 15.

Very few quantitative data are available on the consumptive use for field and truck crops. It is known that in actual practice a large excess of water is applied to truck crops during the seed-germination period and that irrigation efficiency is low.

Farm duty of water--that water which is delivered to the farm headgate--indicates only the total amount of water applied and does not necessarily indicate the irrigation requirement of a given crop. The quantity of water lost by percolation to the water table or by surface runoff is usually not known. Records of water delivered to farms, however, do indicate a general trend of relative duty of water for the several crops (table 9).

Irrigation efficiency[21]

In order to maintain production and to plan an effective drainage system, the worker should not only know the consumptive use of the crops, but also the most effective method of applying the irrigation water and at what frequencies it should be applied. Irrigation frequency depends upon several conditions, such as the water-storage capacity of the soil within the root zone and the demand of the plants upon this reservoir at any given time of year.

Moisture-storage capacity of the soil may be calculated when the following factors are known:

(1) The apparent specific gravity (volume-weight) of the several strata composing the root zone.

(2) The moisture content at the time of irrigation in percent by weight.

(3) The field capacity of the soil, which may vary with depth when associated with a high water table.

The volume-weight may be obtained most easily by securing core specimens of known volume of representative strata, ovendrying the specimen and weighing the soil derived from the known volume, Then,

$$V_w = \frac{\text{Weight of the soil in grams}}{\text{Volume of the soil in cubic centimeters}}$$

The second factor may be determined by field-moisture sampling. These samples are weighed, dried, and reweighed.

$$P_w = \frac{\text{Wet wt. of soil - Dry wt. of soil}}{\text{Dry wt. of soil}}$$

The third factor is very much more difficult to determine in the laboratory, but a series of samples taken in the field 24 to 48 hours following an irrigation will give the desired data.

With these three factors determined, the calculation of the number of inches of irrigation water to apply is made as follows:

$$W = \frac{(Fc_1 - Pw_1) \times Vw_1 \times D_1}{100} + \frac{(Fc_2 - Pw_2) \times Vw_2 \times D_2}{100} + \text{etc --}$$

When W = Irrigation water application in acre-inches per acre (inches depth)

Fc_1, Fc_2 = Field capacity of a soil horizon or stratum (percent by weight)

Pw_1, Pw_2 = Percent by weight of moisture of a soil horizon or stratum

D_1, D_2 = Thickness of a soil horizon or stratum (inches)

Vw_1, Vw_2 = Volume weight of a soil horizon or stratum (ratio)

Now that it is possible to determine with reasonable accuracy how much water may be applied to a given site condition, the question arises as to how it may be applied without causing waste by surface loss or by too much deep percolation beyond the desired 10-percent excess.

The fundamental question raised is, what is the infiltration and subsequent percolation rate of a given site condition? If this factor is known, the problem resolves itself into the design of an irrigation system which will evenly distribute the water over the field and maintain it on a given site for a specified length of time.

In theory this may be possible but practically it is impossible because of the numerous uncontrolled variables. Therefore, it is desired to set up irrigation systems which will most closely conform to these requirements. When consideration is taken of the relationships of the water table to the entry of water into the soil profile, it is found that the rate of water entry is not constant. The entry rate consistently falls during a given irrigation time. Because of this phenomenon, there is some equalizing effect upon those portions of the irrigated area that have excessive ponding periods.

The most effective method of establishing standards of irrigation design is to conduct a series of trial runs on representative slopes and soil types.

Irrigation-run studies

A series of these trials was conducted during 1945 and 1946. They were confined entirely to the border-type irrigation of alfalfa. The procedure used in making these investigations is outlined below:

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[20] Blaney, H. F., Water Requirements of Crops Affecting Irrigation Planning. June 6, 1944. [Typewritten.]

[21] After report by V. S. Aronovici. See footnote 6, p. 2.

1. Selection of plot
   - (a) Stratum survey of the soil profile is made; extremely complex stratifications or irregularities in surface soil should be avoided.
   - (b) Desired length of run is selected.
   - (c) Level survey of the border is made; very uneven or unreasonably low grades should be rejected as not being typical.
2. Preirrigation data
   - (a) Volume weights are obtained of representative soil horizons or strata.
   - (b) If a water table is present, piezometers are installed in the field and water levels observed.
   - (c) Soil-moisture samples of the soil profile are taken at 100- or 150-foot intervals.
   - (d) 100-foot stations are established in the center of the border.
   - (e) Either a Parshall flume or V-notch weir is installed at the head-ditch outlet.
3. The irrigation
   - (a) Estimates are made of the total quantity of water needed to refill the soil reservoir.
   - (b) Water is then introduced into the border at a predetermined rate.
   - (c) As the waterfront progresses down the border, record is kept of the time required to reach each of the stations.
   - (d) When the water is cut off, the time at which the standing water disappears from each station is recorded. From this may be obtained the total ponding time for each station.
   - (e) The total quantity of water applied to the border is calculated. If there is waste water at the lower end of the border, this is measured by a V-notch weir, or estimated.
   - (f) Piezometer observations are made during and directly following the irrigation until a minimum depth is reached and the water table begins to fall.
4. Post irrigation
   - (a) A second series of soil-moisture samples is taken in duplicate to the first, 48 hours following irrigation. From these data may be calculated the total moisture gain for each station.
   - (b) Total ponding time for each station is calculated. From these data may be calculated the mean rate of infiltration.
   - (c) The wave-front pattern is plotted.
   - (d) In order to determine the adequacy of the irrigation with respect to excess requirements for leaching of salts, chloride determinations are made of the soil samples taken before and after irrigation.

A careful study of these data will give an accurate picture of the irrigation under the conditions existing in a given site circumstance (table 10).

Some basic recommendations can be established from these observations:

(1) Good leveling is the most important prerequisite to irrigation efficiency.

(2) Percent of soil moisture at the time of irrigation is very important.

(3) Steeper grades and large head capacity allow for adjustment of irrigation application to meet changing field conditions.

(4) Flat grades and small heads restrict the latitude of application rate and increase the danger of ponding in poorly leveled fields.

(5) Variance of soils within fields and borders precludes set recommendations. Maximum length of runs should be 660 feet for light soils, 1,320 feet for medium soils, and 2,640 feet for heavy soils in the Imperial Valley.

(6) The longer the run the more exacting is the skill needed in determining rate and duration of application.

Tile-Spacing Formula

Not only was the Imperial Valley research project engaged in developing methods of measuring the factors which were important in the analysis of a drainage problem, but it also concerned itself with working out procedures and techniques for applying these data to the various problems encountered in the field.

The phenomenon expressed by the Darcy law ($Q = PIA$) is of utmost significance in the basic solution of drainage problems. If Q, P, and A are known, it is possible to solve for hydraulic gradient I. These factors can be in any unit so long as the units are comparable. This precept was used as a basis in developing a tile-spacing formula.

In the spacing formula, the drawdown or hydraulic gradient about a tile line has been synthesized. Limits to this drawdown curve are established for any site circumstance, then a determination is made of the tile spacing needed to produce the desired drawdown. The Darcy law concept is used in several other ways: (1) To determine the amounts of seepage, (2) to predict the effect of pumping from wells or sumps, and (3) to predict the amounts of leachate passing through leached areas.

Symbols used

Q = quantity of water discharged from one tile line in gallons per day per foot of tile line

Q_R = flow towards the tile line at any point out from the line, gallons per day per foot of tile line

Q_t = total discharge from the field, gallons per day per foot of tile line

P = coefficient of permeability, gallons per square foot per day

I = hydraulic gradient (dy/dx on the drawdown curve)

TABLE 10.—Summary of field irrigation-efficiency studies, Imperial Valley, Calif.

(Measurements made by V. S. Aronovici)

Farm	Surface texture[1]	Length of run	Grade	Application rate	Amount applied	Soil moisture gain	Consumptive use	Total gain	Average wave velocity[2]	Water table depth before irrigation	Water table depth after irrigation	Water table rise	Salinity before irrigation	Salinity after irrigation	Irrigation efficiency
		Feet	*Per-cent*	*C.f.s.*	*Inches per acre*	*Inches per acre*	*Inches per acre*[3]	*Inches per acre*	*Feet per min.*	*Feet*	*Feet*	*Feet*	*P.p.m. cl*	*P.p.m. cl*	*Percent*
Waterman 12/29/45	Si CL	575	0.20	0.66	1.85	1.19	0.50	1.69	3.12	None	None	0	--	--	91.4
Rood 3/22/46	Si CL	610	.07	2.40	3.94	1.09	1.26	2.35	4.0	--	--	--	180.8	163.1	59.6
Dorman 11/15/44	LS	710	.28	2.14	3.65	4.18	.59	4.77	9.8	4.76	3.58	1.52	46.3	48.3	--
Dorman 11/19/44	LS	710	.28	2.24	2.49	2.75	.32	3.07	7.6	4.74	3.11	1.63	38.6	47.1	--
Waterman 12/28/45	Si CL	1,200	.20	1.23	2.88	2.29	.45	2.74	4.9	None	None	--	--	--	98.5
Ross L-3 2/25/46	Si CL	1,200	.09	1.28	3.66	2.09	.90	2.99	1.82	3.40	2.70	.70	--	--	81.6
Ross L-5 2/25/46	Si CL	1,200	.05	2.07	4.40	2.11	.90	3.01	2.81	3.36	2.48	.88	82.6	73.8	68.4
Ross L-5 3/15/46	Si CL	1,200	.05	5.01	3.52	1.33	.70	2.03	3.45	3.09	2.34	.75	--	--	57.6
Freedman 4/29/46	Si CL	1,200	.04	2.19	4.57	3.78	.58	4.36	3.67	None	None	0	--	--	95.0
Rood 3/20/46	Si CL	1,200	.15	1.98	3.36	1.20	1.26	2.46	4.7	3.16	1.05	2.11	180.8	163.1	73.6

[1] Si CL = Silty clay loam; LS = loamy sand.
[2] Rate of forward motion of wave front down the run.
[3] Estimate of consumptive use between first and second soil sampling.

A = cross-sectional area through which water flows to the tile (y x 1-foot section (fig. 12)).
S = spacing of the tile lines (feet)
c = constant
C = constant of integration
a = distance from the average tile depth to barrier stratum (feet)
b = distance from drawdown curve to barrier stratum at the midpoint between the tile lines (feet)
y = distance from any point on the drawdown curve to the barrier stratum (feet)
x = distance out from tile line to any point on the drawdown curve
W = width of field to be tiled (feet)

Development of formula

A basic assumption has been made in developing the tile-spacing formula. In figure 12 where lines are spaced a definite distance, S, all the flow to the tile is due to the removal of water from a strip of soil 1 foot thick extending a distance $S/2$ on each side of the tile line. The assumption is that the horizontal flow, Q_R, at any distance, x, is proportional to the distance from a point midway between the tile lines where the flow is zero. When $x = 0$, flow toward the tile line is one-half the flow in the tile line, or $Q/2$. Therefore, Q_R at any point at right angles to the line is

$$Q_R = (c) \quad (S/2 - x)$$

When $x = o \quad Q_R = Q/q$, so that $c = \frac{Q}{S}$

then $Q_R = \quad Q/S \quad (S/2 - x)$

From figure 12

$$I = dy/dx$$

and

$$A = (y) \quad (\text{1-foot section})$$

Substituting these values in the Darcy equation:

$$Q/S \; (S/2 - x) = (P) \; (y) \; \frac{(dy)}{(dx)}$$

from which

$$\frac{Q}{2PS} \int (S - 2\,x)\; dx = \int y \; dy$$

integrating

$$-\frac{Q}{8PS} \; (S^2 - 4Sx + 4x^2) = \frac{y^2}{2} + C$$

when

$$x = 0, \; y = a, \; \text{so}$$

$$C = -\frac{Q\;S}{8\;P} - \frac{a^2}{2}$$

and thus

$$\frac{Q}{8PS} \; (S^2 - 4Sx + 4x^2) = \frac{y^2}{2} + (\frac{QS}{8P} - \frac{a^2}{2})$$

Solving for P:

$$P = \frac{Q}{S} \; \frac{(Sx - x^2)}{(y^2 - a^2)}$$

and when

$$x = S/2, \; y = b$$

so that

$$P = \frac{QS}{4 \; (b^2 - a^2)}$$

or, solving for S,

$$S = \frac{4\;P\;(b^2 - a^2)}{Q}$$

which is the simple form of the spacing formula. The spacing is thus expressed in terms of the coefficient of permeability (mean transmission constant) of the aquifer, the amount of water to be removed, and the site circumstance of the drawdown curve.

For purposes of simplifying spacing calculations, this basic formula has been modified.

Heretofore three or four trial calculations have had to be made to secure spacing since total Q_t must be proportioned to an estimated tile spacing. However, since the quantity Q in the formula is the Q from one tile line, it is only a portion of the total quantity Q_t to be drained from the field.

Thus Q is equal to Q_t multiplied by a factor. This factor is, in reality, spacing (S) divided by width (W) of the field to be tiled.

Then $Q = \frac{Q_t\;S}{W}$ = quantity of water discharged in gallons per day per foot of tile line

Substituting this in the formula, the equation becomes

$$S = \frac{4\;P\;(b^2 - a^2)}{\frac{Q_t\;S}{W}},$$

or

$$S^2 = \frac{4\;P\;(b^2 - a^2)}{Q_t/W}$$

Only one calculation is needed and no prescribed limits are necessary regarding the dimensions of the field. This is the formula now used in tile spacing design.

Testing the formula

Many tests have been made both in the field and in the laboratory to check the validity of this basic concept.

Laboratory.--The laboratory work on this project was done in a sheet-iron tank 12 feet 6 inches long, 5 feet high, and 2 feet 10 inches wide (fig. 13).

In the middle and along the end walls of this tank and parallel to them and to the floor, three sets of drains were placed at heights 13, 36, and 59 centimeters above the floor. Each drain had a diameter of 5 centimeters. Inside the tank the drains consisted of galvanized sheet-iron pipes perforated with saw-cut slits at random 1/2-

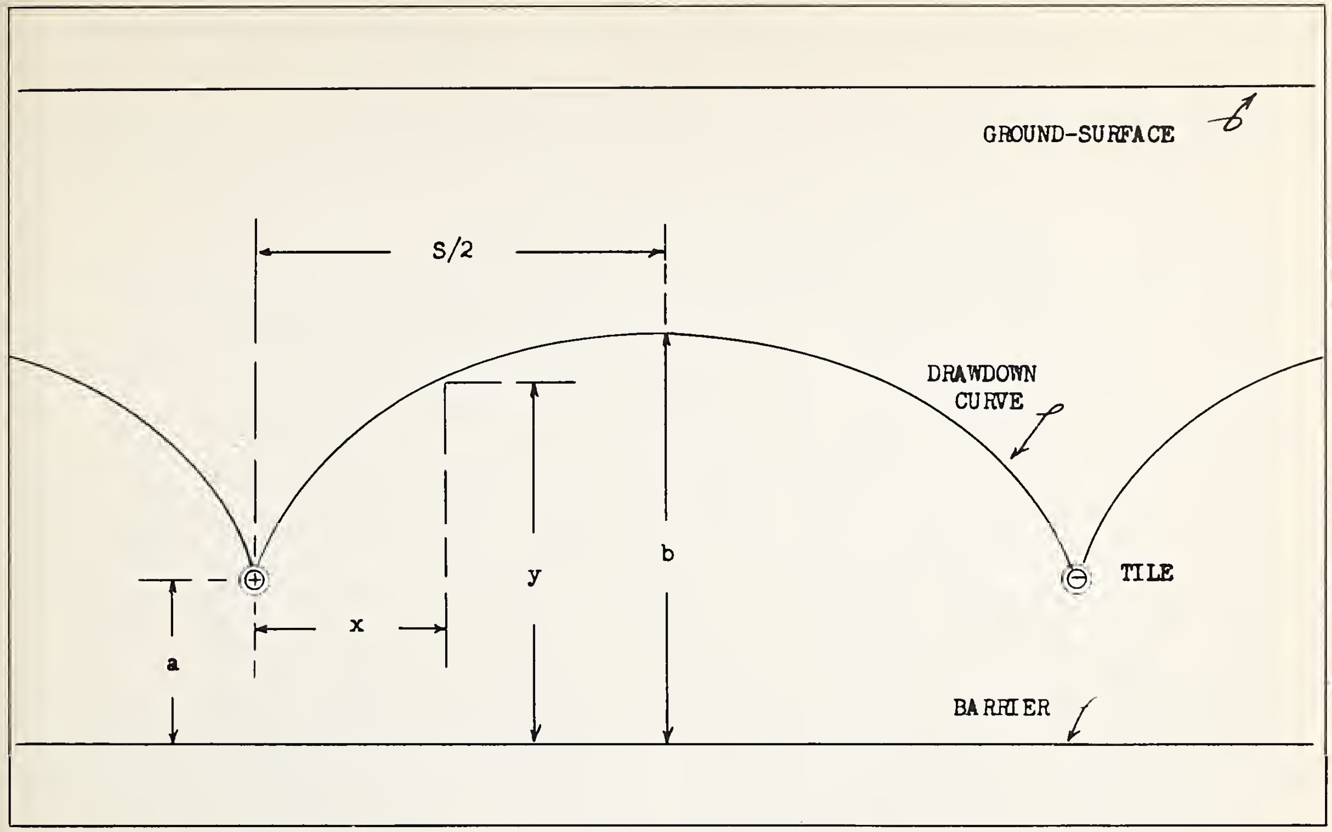

Figure 12.--Development of tile-spacing formula.

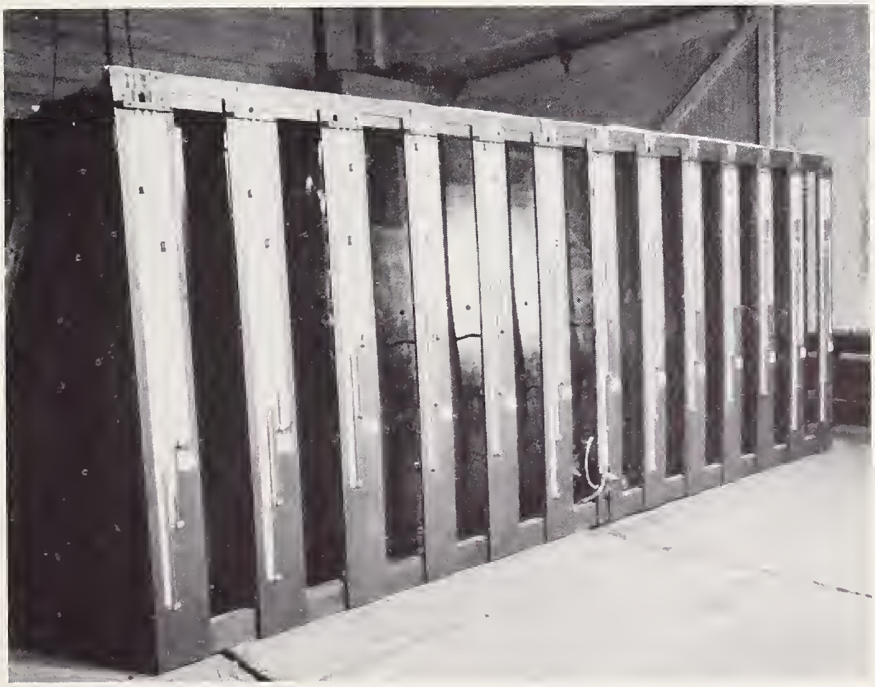

Figure 13.--Laboratory tank used for tile-spacing trials

TABLE 11.--Laboratory check of tile-spacing formula. Trial No. 16--Left bottom tile line. Actual spacing 751 cm., Imperial Valley, Calif., drainage investigation

Date and time	Q per cm. width	P coefficient of permeability	Corrected b[1]		Corrected a[1]		(b^2 - a^2)	Computed spacing (using corrections)
			b	b^2	a	a^2		
Jan. 24, 1946								
10:00 (a.m.) start:	Cc./hr.	Cc./cm.^{2}/hr.	Cm.	Cm.^{2}	Cm.	Cm.^{2}	Cm.^{2}	Cm.
13:15	320	4.0	143.0	20,420	77.5	6,000	14,420	723
14:15	300	4.0	139.5	19,450	77.5	6,000	13,450	720
15:08	280	4.0	136.2	18,580	77.5	6,000	12,580	720
15.40	262	4.0	134.5	18,100	77.5	6,000	12,100	740
16:35	254	4.0	133.0	17,690	77.5	6,000	11,690	737
Jan. 25, 1946								
8:04	131	4.0	111.1	12,350	77.5	6,000	6,350	775
11:30	122	4.0	109.5	12,000	77.5	6,000	6,000	787
14:30	115	4.0	107.8	11,600	77.5	6,000	5,600	780
16:00	110	4.0	106.8	11,400	77.5	6,000	5,400	785
Jan. 26, 1946								
9:00	67	4.0	96.0	9,220	77.5	6,000	3,220	768
Jan. 27, 1946								
10:30	45	4.0	90.5	8,200	77.5	6,000	2,200	780
Jan. 28, 1946								
8:30	26	4.0	85.6	7,320	77.5	6,000	1,320	755
Jan. 29, 1946								
9:31	15	4.0	82.2	6,750	77.5	6,000	750	798

[1] Corrections include adding 65 cm to the manometer readings at "a" and "b" to allow for the flow laterally in the capillary fringe above the water table.

inch spacing. They were attached to 1-inch holes tapped through the tank wall and were controlled by gate valves on the outside of the tank.

A series of manometer-takeoff tubes were placed on the opposite side of the tank. The tubes were let out via rubber attachments to glass manometers. Thirteen sets of manometers were installed, consisting of either 3 or 4 units at 9-inch vertical spacing, with 1-foot horizontal spacing. The manometers totaled 40. This assembly gave a comprehensive coverage of the hydrostatic-pressure potential over the lower one-half of the tank. The drawdown of the phreatic surface within the tank, when one or more of the drain lines was opened, is indicated by the height of the water in the manometers outside the tank. The tank was also equipped with an intake valve and a perforated intake pipe which entered at the center bottom and laid on the floor.

The sands were tamped into the tank and in-place-permeameter samples taken at various levels during the filling. From 12 to 15 horizontal and vertical inplace samples and packed samples of the material placed in the tank were used in calculating an overall coefficient of permeability for the soil.

The soil material in the tank was then saturated with tapwater very slowly from the bottom intake upward. In each instance where a new trial run was made, the water level in the tank was allowed to stabilize for a time before the run was made. This allowed most of the remaining air to dissolve out of the soil pores.

When the material in the tank was completely saturated and the water table was at or near the surface of the soil and had become stabilized, the tank was ready for a trial run. Then one of the drain-line valves was opened and measurements were made of the rate of flow out of the drain. At the same time readings were made of the water columns in the manometers across the face of the tank. These figures gave the variable elements of the tile-spacing formula, and calculations were made for spacing.

In making the trial in the tank the following variables were measurable:

(1) P = coefficient of permeability (cc./cm.^{2}/hr.)
(2) Q = effluent from the drain line(cc./hr.)
(3) b = height of drawdown curve at mid-point between (cm.) drains (from manometers)
(4) a = height of drain from impervious layer (tank floor) (cm.)
(5) Spacing of drains (cm.)

Space does not permit a discussion of all the difficulties encountered in making checks of the tile-spacing formula in the laboratory (4). Suffice it to say that when corrections were made to take care of lateral flow in the capillary fringes above the phreatic water table, very close correlations were obtained between actual spacing and spacing as calculated by the project formula (table 11).

Field trials. --Many reconnaissance surveys were made in an effort to find field sites of

TABLE 12.--Results of field trials of a tile spacing in Imperial Valley.

Trial	Date	Tile effluent		Actual spacing of lines	b	b^2	a	a^2	b^2-a^2	Coefficiency of permeability (P)	Computed spacing
		Q	Q								
		Gal./day	*Gal./ft.*	*Feet*	*Feet*	*Sq. ft.*	*Feet*	*Sq. ft.*	*Sq. ft*	*Gallons*[1]	*Feet*
1.....	June 23	8,208	6.42	600	5.09	25.90	2.65	7.03	18.87	60.0	705
2.....	June 24	7,488	5.84	600	4.66	21.70	2.65	7.03	14.67	60.0	605
3.....	June 25	43,200	33.80	300	7.25	52.60	2.65	7.03	45.57	60.0	324
4.....	June 26	30,816	24.10	300	6.52	42.50	2.65	7.03	35.47	60.0	354
5.....	March 5	1,540	1.28	350	4.10	16.81	1.50	2.25	14.56	9.0	410
6.....	March 5	1,200	1.00	370	4.35	18.90	1.20	1.44	17.46	6.0	418
7.....	March 5	1,710	1.55	390	5.25	27.56	2.00	4.00	23.56	6.5	394
8.....	March 11	2,600	2.16	350	4.50	20.25	1.50	2.25	18.00	9.0	300
9.....	March 11	2,215	1.84	370	5.10	26.00	1.20	1.44	24.56	6.0	321
10.....	March 11	2,420	2.20	390	5.95	35.40	2.00	4.00	31.40	6.5	372
11.....	April 25	1,124	.94	350	3.35	11.25	1.50	2.25	9.00	9.0	345
12.....	April 25	883	.73	370	3.60	12.95	1.20	1.44	11.57	6.0	379
13.....	April 25	950	.86	390	4.20	17.65	2.00	4.00	13.65	6.5	412

[1] Gallons per foot per day per foot square.

existing tile systems where field checks could be made of the project formula. The minimum requirements of these field sites were as follows:

(1) The tile effluent must be measurable for individual lines or the tile system must be homogeneous enough to permit proration of the flow to individual lines.

(2) The location and depth of the lines must be known.

(3) The soil conditions should be relatively homogeneous with a barrier below the tile lines.

(4) Extraneous seepage in or out of the plot should be minimum.

While these requirements might seem to be out of proportion, especially regarding soil conditions, it was felt that the formula should be given a trial on the simple profiles first.

The project has made a number of these field trials of the spacing formula (table 12). Tile systems were analyzed where the lines emptied individually into an open drain. Thus, we could determine accurately the amount *(Q)* of effluent drainage from the tile lines. A system of piezometers was installed adjacent to and out from these individual lines and tests were made of the permeability of the aquifer being drained by the tiles. The lines were accurately located within the soil profile to determine the "b" and "a" factors of the formula. With these factors known, actual spacing was compared with calculated spacing. All the field trials were satisfactory.

INVESTIGATIONS 1947-50[22]

The research work carried on from 1943 to 1947 resulted in the analysis of the basic fundamental procedures for determining the causes and extent of the drainage problem on individual farms. It culminated in the development of tools and techniques for solving these drainage problems. The subsequent years were spent by the Division of Irrigation Engineering and Water Conservation in cooperation with Soil Conservation Service--Operations and the Imperial Irrigation District in an attempt to refine, streamline, and put into practical use these various techniques.

Yearly progress reports[23] [24] [25] have been written covering these investigations. The emphasis of these last 4 years was to expand the work valley-wide and get the research out of the laboratory and into the field for practical everyday application.

Design of Tile Systems

The procedure for designing tile systems in Imperial Valley is based on an analysis of the Darcy Law. As has been detailed in the previous chapters of this report, the design of tile spacing is dependent upon quantitative measurement of: *(1)* The depth and extent of the various soil strata *(A)*; (2) the permeability of those soils *(P)*; (3) the hydraulic gradient of the water table *(I)*; and (4) the estimate of quantity of water to be drained *(Q)*.

The spacing of the tile lines can be ascertained from these four components.

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[22] Investigations conducted by W. W. Donnan and G. B. Bradshaw under the supervision of Harry F. Blaney.

[23] Donnan, W. W., and Bradshaw, G. B. Progress Report on Cooperative Investigations in Imperial Valley, California, for the year 1947. [Typewritten.]

[24] Donnan, W. W. and Bradshaw, G. B. Progress Report on Cooperative Investigations in Imperial Valley, California, for the year 1948. [Typewritten.]

[25] Bradshaw, G. B., and Donnan, W. W. Progress Report on Cooperative Investigations in Imperial Valley, California, for the year 1949. [Typewritten.]

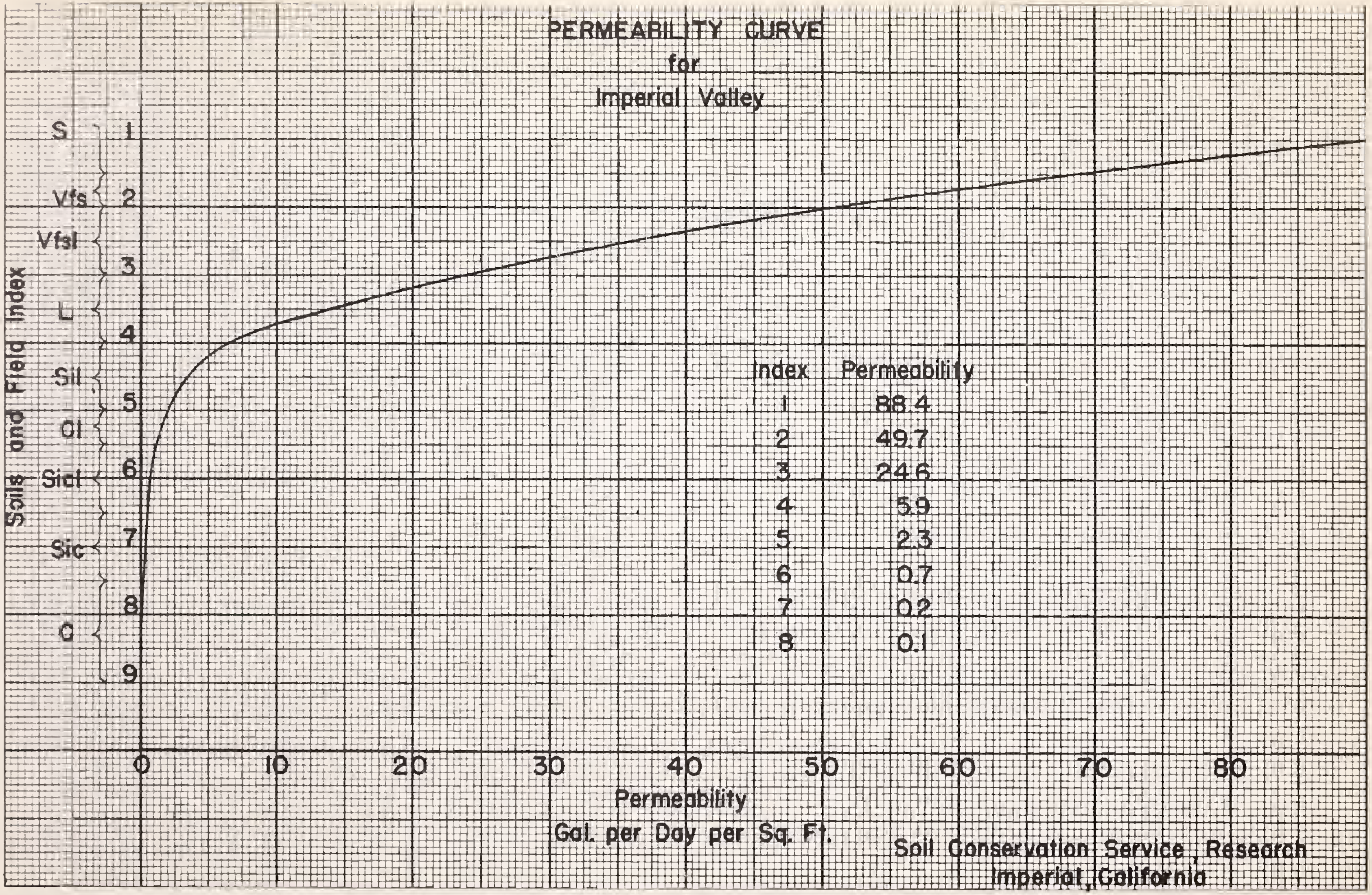

Figure 14.--Permeability curve for Imperial Valley, Calif.

Investigation methods

In the farm-conservation planning work of the Soil Conservation Service, the drainage problems are investigated about as follows: Holes are bored in a grid to a depth of about 9 feet with a soil auger. Enough holes are bored by the technician to prepare a conservation-survey map and to be able to indicate by symbol the thickness, depth, and texture character of the 9-foot profile of the area to be tiled. The soil permeability of each strata of the soil mapped is determined by relating the texture characteristic to an index curve similar to figure 14. This curve has been prepared to circumvent the necessity for making laboratory-mechanical analyses of silt-plus-clay content of the soil sample. This curve relates permeability of the soil stratum to the texture of the soil and to the permeagraph-index number as mapped in the field by the soil surveyor. When a hole is bored, the strata are classified by texture and then related to the curve to secure an approximate value of permeability. The relationships depicted by figure 14 are based on laboratory and field analysis, together with a great many actual permeability runs on soil samples. The wide latitude outlined in figure 14 makes ample field judgment possible and yet restricts estimates to consistent ranges. It should be noted that this curve is applicable only to the Imperial Valley soils.

Falling-head permeameter

When soil textures are difficult to distinguish, samples are analyzed by a mechanical analysis and indexed to permeability coefficients in the laboratory. In addition, direct methods of getting permeability are still being investigated. One of these methods is embodied in a falling-head permeameter apparatus (fig. 15).[26] The devices in figure 15 are modeled on an apparatus designed by Thesis (19) for use in connection with ground-water investigations in New Mexico. The device being used in the Imperial Valley investigations consists of a 2-inch brass soil cylinder connected at the base with a small copper U-tube to which is attached a graduated glass tube. An auxiliary water-supply cylinder is connected to the U-tube to supply water for saturating the soil. Soil is either packed in the 2-inch brass cylinder or samples are taken in-place, since the cylinder is demountable. Water is introduced via the supply tube until the sample is saturated and water is discharging over the top rim of the brass cylinder. Then the supply valve is turned off and the rate of drop of the water in the graduated glass tube is noted. This rate of drop is an indication of the transmissibility of the soil. From the Darcy Law (3) a formula has been derived, in which:

$$P = 2.30259 \frac{d^2}{D^2} \frac{(L)}{t} \log \frac{h_o}{10\,h} \times (3600)$$

where:

P = coefficient of permeability in cc./cm.^{2}/hr.
d = diameter of the glass tube in cm.
D = diameter of the soil tube in cm.
L = length of the soil tube in cm.
t = time of fall of water from h_o to h in seconds.
h_o = initial head in cm.
h = final head in cm.

Temperature correction.--The coefficient of permeability obtained using this formula is defined for a water temperature of 60° F. If the test is run with water of any other temperature, the permeability may be corrected by multiplying the right side of the equation by the proper correction factor[27] which is given below.

Water temperature (°F.)	Conversion factor (C_t)	Water temperature (°F.)	Conversion factor (C_t)	Water temperature (°F.)	Conversion factor (C_t)
40	1.37	54	1.09	68	0.89
41	1.35	55	1.08	69	.88
42	1.33	56	1.06	70	.87
43	1.31	57	1.04	71	.86
44	1.28	58	1.03	72	.85
45	1.26	59	1.01	73	.84
46	1.24	60	1.00	74	.83
47	1.22	61	.99	75	.82
48	1.20	62	.97	76	.81
49	1.18	63	.96	77	.80
50	1.16	64	.95	78	.79
51	1.15	65	.93	79	.78
52	1.13	66	.92	80	.77
53	1.11	67	.91	--	--

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[26] Bradshaw, G. B., and Donnan, W. W. A Falling Head Permeameter for Evaluating Permeability. January 1950. [mimeographed.]

[27] See table p. 62 of reference (19).

Results of tests.--The most reliable and consistent results have been obtained by running tests of soil samples taken inplace. Samples can be laboratory packed, but it is difficult to obtain the same degree of compaction in all samples. Comparative test runs with inplace and packed samples reveal that for sand there is a fair correlation, but for heavy-textured soils the difference in results might vary 500 percent. On the other hand, inplace samples can be relied upon to give a consistent measurement of the permeability coefficient.

In using the inplace technique for drainage investigations, it has been found expedient to take both horizontal and vertical samples. The flow of water horizontally through the soil is often much greater than flow vertically. This is due to the lath-like deposition of soil particles. The soil particles are usually bedded into microscopic strata which tend to impede vertical flow. This impediment is not so evident in the horizontal direction, and thus the horizontal inplace samples tend to give higher coefficients. Since in drainage most of the flow to a tile line or an open drain is in the horizontal direction, this factor is important.

There may be some question as to whether a short-term test run, as proposed in this technique, would give a true indication of the actual coefficient of permeability of the soil being tested. Many research workers have felt that the only true test of the flow of water through the soil requires a run of several days. Table 13 is a compilation of data on 26 different inplace tests of hydraulic permeability.[28] Note that these runs were carried on for periods ranging from 96 hours to 906 hours. Yet the measured coefficients of permeability at the start of the runs was, in a majority of the tests, only slightly different from the actual average determined coefficient based on all the observations during the run. Thus it has been concluded that a test run of about 1 hour with inplace samples in the falling-head permeameter will give a good measurement of the coefficient of permeability of the soil.

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[28] See footnote 4, p. 2

TABLE 13.--Results of long-term measurements of coefficient of permeability of soils, Imperial Valley, Calif.[1]

Sample No.	Total hours of run	Coefficient of permeability Cubic centimeters per square centimeter per hour		
		Start of run	End of run	Average[2]
46-C1	214	18.65	14.72	17.00
46-E2	186	3.13	5.42	4.78
46-E3	188	7.10	11.40	10.85
46-D1	165	11.00	11.50	11.12
46-D2	120	11.59	7.55	8.55
96-A1	284	1.15	1.57	1.37
96-A2	284	.62	2.30	1.31
96-B	284	.73	1.68	1.23
122-A	310	14.08	14.05	13.95
122-B	96	7.89	8.68	8.42
122-C	906	12.75	7.50	9.14
123-A	117	11.75	16.50	11.50
123-B	116	12.05	11.05	11.85
123-B	342	13.80	10.44	12.15
123-C	146	8.67	11.49	9.43
123-C	169	8.68	6.52	7.36
125-A	162	13.70	14.95	14.22
125-B	841	8.85	7.14	8.65
149-A	340	10.90	7.91	10.13
149-B	362	7.78	8.40	8.09
149-C	339	11.30	13.40	11.51
150-A	303	18.10	21.80	22.41
150-B	339	7.46	6.45	8.23
213-A	483	.77	.56	.71
213-B	146	1.45	1.73	1.47
213-C	479	1.06	.75	1.03

[1] Data taken from table 1, p. 102, appendix B-6 of Preliminary Progress Report of Cooperative Investigations in Imperial Valley, California, 1933-44 by W. W. Fox, V. S. Aronovici, and W. W. Donnan.

[2] Average based on all observations taken during the test.

Water-table depth

The stratum survey may reveal evidence of water-table depth at the time of the survey. Reasonably accurate estimates of the water-table depth may be accomplished if the strata are coarse textured. Usually, sandy material will slough rapidly into the auger hole directly above the free-water surface. Determination of the water-table depth in the fine textures is more difficult. In clay soils, a boring should be allowed to remain open overnight before a measurement is made.

Considerable difference in observed water-table elevations may occur, depending on the texture of the material in which the auger hole terminates. Borings terminating in sandy material will indicate a higher water table owing to the rapid flow of water into the boring. When there is any doubt, the piezometer is used in measuring the position of the water table for detailed farm planning.

When piezometers are used, the axis of the line of observations is generally located at right angles to the canal bordering the property or the drain or some other topographical feature suspected of influencing the water table. The longer the observations can be carried out the more reliable will be the record for analysis. However, observations over one or more irrigation cycles usually indicate trends and provide the farm-conservation planner with enough information to assist in the design of remedial measures.

Quantity of water to be drained

In the foregoing discussions it has been pointed out that for drainage of irrigated land it is advantageous to know how much water must be drained down and out of the problem area in order to keep the salt balance and to lower the water table to a safe level. The quantity of water to be drained is dependent on a multitude of complex interrelationships of soil-water hydrology. All the various factors, such as irrigation head, length of run, slope, soil type, ponding time, waste disposal, crop type, infiltration rate, evapotranspiration, and seepage in and out of the problem area, enter into the final calculation of the amount of water which must be drained by the facility.

It is important to know how much water is being dealt with, not as an aid in recommending tile size but in order to determine intelligently the spacing of the lines. If the designer knows the permeability of the soil he can so space his lines that drainage will be accomplished.

It has been determined that, of the major crops grown in the Imperial Valley, alfalfa, on a yearly basis, uses the largest amount of water. (Some double-cropping combinations may use slightly more water in any one year, but since alfalfa is the most widely grown crop it is used for general-design purposes.) Other research agencies have estimated that 8 to 12 percent of the water applied must drain down and out of any cropped-area root zone in order to maintain a favorable salt balance in the soil. Therefore 10 percent of the water applied may be considered the amount to be dealt with in the design of the drainage system. Part of this 10 percent may drain out of the area naturally, thus reducing the amount which must find outlet through the designed system. On the other hand, extraneous seepage or artesian pressure may augment the 10 percent. Therefore, the technician makes an inventory and reviews all the available physical water-use data and piezometric information concerning the problem area before estimating the excess percent to use in his design.

The following tabulation is a calculation of the net excess, by percentages, for alfalfa:

Net excess Percent	Quantity of water to be drained (Qd) Gal. /sq. ft. /day
2	0.0036
4	.0072
6	.0108
8	.0144
10	.0180
12	.0216
14	.0252
16	.0288
18	.0324

This tabulation is based on the following: (a) An average duty of water for alfalfa of 4.8 acre-feet per year; (b) a 10-percent surface waste; (c) 12 irrigations annually; and (d) a 15-day irrigation cycle. If the farmer has records of water use, it may be advantageous to accept either (a) his annual amount applied in lieu of the valley average, or (b) his peak irrigation-application rates during the early summer months and his cycle of days, in apportioning the daily amount of water to be drained by the proposed system.

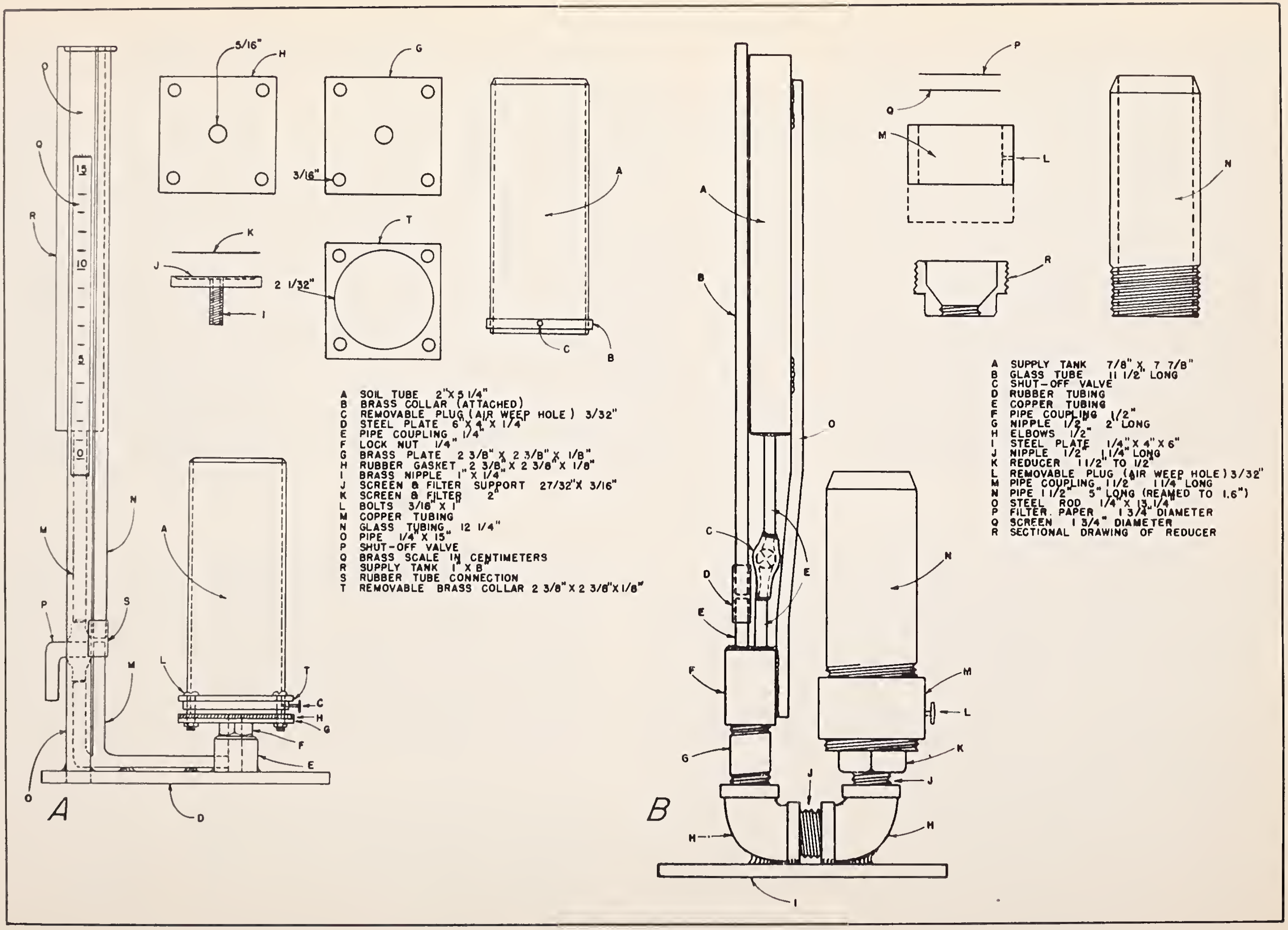
The guides for estimating the quantity of water to be drained *(Qd)* are not to be regarded as unchangeable. Both Research and Operations are working on this complex factor and hope to develop a less empirical procedure.

Design Procedure

When all the investigational work on a farm-drainage problem has been completed, the tile system is designed. There are three types of tile systems recommended for use in the Imperial Valley: (1) Grid system, (2) barrier-drainage system, and (3) intercepting-drain system. Each of these is often used separately or in combination in the overall farm plan.

Grid system

The most widely used design is called the grid system. The tile lines are laid out in the form of a series of parallel laterals connected to a main collecting line, which empties into



A
B
5/16"
3/16"
2 1/32"
15
10
5
0
A SOIL TUBE 2" X 5 1/4"
B BRASS COLLAR (ATTACHED)
C REMOVABLE PLUG (AIR WEEP HOLE) 3/32"
D STEEL PLATE 6" X 4" X 1/4"
E PIPE COUPLING 1/4"
F LOCK NUT 1/4"
G BRASS PLATE 2 3/8" X 2 3/8" X 1/8"
H RUBBER GASKET 2 3/8" X 2 3/8" X 1/8"
I BRASS NIPPLE 1" X 1/4"
J SCREEN & FILTER SUPPORT 27/32" X 3/16"
K SCREEN & FILTER 2"
L BOLTS 3/16" X 1"
M COPPER TUBING
N GLASS TUBING 12 1/4"
O PIPE 1/4" X 15"
P SHUT-OFF VALVE
Q BRASS SCALE IN CENTIMETERS
R SUPPLY TANK 1" X 8"
S RUBBER TUBE CONNECTION
T REMOVABLE BRASS COLLAR 2 3/8" X 2 3/8" X 1/8"
A SUPPLY TANK 7/8" X 7 7/8"
B GLASS TUBE 11 1/2" LONG
C SHUT-OFF VALVE
D RUBBER TUBING
E COPPER TUBING
F PIPE COUPLING 1/2"
G NIPPLE 1/2" 2" LONG
H ELBOWS 1/2"
I STEEL PLATE 1/4" X 4" X 6"
J NIPPLE 1/2" 1 1/4" LONG
K REDUCER 1 1/2" TO 1/2"
L REMOVABLE PLUG (AIR WEEP HOLE) 3/32"
M PIPE COUPLING 1 1/2" 1 1/4 LONG
N PIPE 1 1/2" 5" LONG (REAMED TO 1.6")
O STEEL ROD 1/4" X 13 1/4"
P FILTER PAPER 1 3/4" DIAMETER
Q SCREEN 1 3/4" DIAMETER
R SECTIONAL DRAWING OF REDUCER

Figure 15.--Falling head-type permeameters the open drain. Grid systems are recommended where soil borings indicate a predominance of strata of sands and sandy loams in the 2- to 8-foot zone of the subsurface.

Grade. --Tile-line grades in grid systems are maintained at a minimum slope of 1 foot per 1,000 feet. It has been found by experience, that the lines silt up or otherwise tend to clog where the slopes are less than 0.001. Where the topography permits, grades steeper than 0.001 minimize any irregularities in the mechanics of laying the lines. In changing grade a flatter gradient is never proposed, because any sediments carried by the velocities of the steeper grade will tend to be dropped in the flatter grade and cause silting. Where the lateral line joins the collecting line, a drop of 0.25 foot is provided. This insures absolute drainage of the lateral into the collecting line. In order to maintain depth in the lateral line when the cross slope of the field is less than 0.001, the designer may find it necessary to angle the laterals on a herringbone pattern. The desirability of manholes at the junction of any 2 lines is debatable. Manholes are advantageous for inspection and maintenance, but unless they are buried, they impede cropping operations. Moreover, the cost of manholes may not be justified where laterals are spaced closely.

Depth. --Depth of line is an important factor in the drainage of irrigated land because of the almost universal salinity of the ground water. Thus, the tile lines must be placed at depths approaching 6 feet, or more, to produce a water-table depth of 4 or 4.5 feet midway between tile lines. In most designs, the depth of the lateral lines is dependent on outlet depth, general slope of the ground surface, and, to a minor degree, the depth to the barrier.

In considering the outlet depth, the designer usually allows at least a 6-inch overpour into the open-drain flow line. This will insure free flow from the tile outlet during periods when the open drain is carrying waste water, and will also allow for some fluctuation in bottom depth of the open drain between cleaning periods. The outlet depth dictates the depth of lines in the grid system. Where outlets are shallow, the designer may consider outletting into a sump to get increased depth. The water is then lifted by automatic pump into the open drain.

It is sometimes difficult to keep the lateral lines at optimum depths where the ground-surface slopes are flat. Since a minimum grade of 0.001 should be maintained by the tile line, the lateral in many cases will tend to become shallow toward the upper reaches of the system. When the lateral-line depth decreases to 4.5 feet or less, it is questionable whether the tile should be installed.

Tile spacing. --The correct spacing of tile lines in irrigated areas is important for economy. Deep-laid tile lines are costly and the reduction of even two or three lines in a grid results in considerable saving.

The spacing of tile laterals is determined by using the formula developed during the early years of the research study.

If a detailed investigation of the drainage-problem area has been made, the designer has enough information to make a calculation of tile-line spacing using this formula. The stratum survey determines the extent of the drainable aquifers and indicates their average permeability. Analysis of the borings made by the soils technician determines the average depth of the barrier stratum. If no substantial barrier is located, the designer assumes a depth to barrier to be twice the depth of the tile lines; that is, about 12 to 14 feet. Positioning of the average barrier and average depth of the tile system indicates the value to be assigned to the "a" factor in the formula. The drainage system is designed for a water-table depth of 4 to 4-1/2 feet at the midpoint between tile lines. This choice will set the value of the "b" factor in the formula. It remains for the designer to exercise his best judgment in deciding upon the quantity of water to be drained *(Qd)*.

A calculation is then made for spacing. Further to simplify this procedure, curves have been prepared (fig. 16). This graph has been drawn for the 2 tile-depth averages most commonly used in the Imperial Valley (5.5 feet and 6.5 feet), and for both the 4-foot and the 4.5-foot midpoint depth of water table.

Spacing examples. --The use of this graph is illustrated as follows:

Example 1. Average overall coefficient of permeability *(P)* of the soil, 25 gallons per square foot per day; average depth of barrier, 10 feet; average quantity of water to be drained, *(Qd)*, 0.018 gallon per square foot per day (10-percent excess); average tile depth, 5.5 feet. The problem is to design for a depth to water table of 4 feet at the midpoint between lines. Referring to figure 16, start with the permeability of 25, go vertically upward to the quantity curves and intersect the 10-percent *Qd* line, thence left to the barrier-depth curve of 10 feet and up to the spacing as shown for a 4-foot midpoint depth of water table. The spacing will be a little over 300 feet.

Example 2. Average overall permeability of 33 gallons per square foot per day; average barrier depth unknown (assume 2 times average tile depth of 6.5 feet, or 13 feet to barrier; average quantity of water to be drained, 0.0198 gallon per square foot per day (11 percent). The problem is to design for a depth to water table of 4.5 feet at the midpoint between tile lines. Start with a permeability of 33, go vertically up to the 11 percent *Qd* line, then right to the 13-foot barrier line, and then down to the spacing of 450 feet.

Planning the system. --After the designer has made a calculation of spacing, he is ready to plan the drainage-grid system. Since averages for the whole problem area or field are used to secure the data for making the spacing calculation, an average tile spacing for the whole field is the result. By analyzing the soil borings, it is possible to increase the spacing in the lighter textured soil areas and decrease the spacing where there is reason to suspect that more tile would be advantageous. If piezometers indicate a definite source of seepage, the design provides for maximum drainage at the indicated point.

The final design takes into consideration all features which the reconnaissance and detailed surveys have revealed to be contributary to the problem. Some rules of design are as follows:

(a) Only one outlet is made for each 1/2-mile of district-owned open drain.

(b) Lateral lines are placed across the direction of flow of the underground water, if at all feasible.

(c) An open drain along any side of the property to be drained is considered a tile line, and the first designed line would thus be located one space distant from the open drain.

(d) Outlets are never located through rows of trees nor is a lateral line located adjacent to a windbreak. Tree roots will clog tile lines.

Size recommendations. --The following tile-size recommendations are used as a guide:

(a) Lateral lines should be at least 4 inches in diameter.

(b) The downstream diameter of any lateral line longer than 1,320 feet should be at least 5 inches.

(c) Collecting lines should not be less than 6 inches in diameter.

(d) The downstream portion of any collecting line at the point where the aggregate lineal feet of upstream lateral lines exceeds 15,000 feet should be at least 8 inches in diameter.

The foregoing tile-size recommendations are the minimum requirements for the Imperial Valley. It should be pointed out that there are several distinct advantages to using larger tile sizes. In view of the small difference in cost of 4-inch, 5-inch, and 6-inch tile, the advantages of larger sizes often outweigh the added cost. Larger sizes will, of course, carry greater volumes of flow. This factor is important when leaching becomes a part of the reclamation. Larger sizes also require less exacting excavation standards. This factor is important where grades are flat. Larger sizes are less likely to silt up, thus cutting maintenance costs.

Drainage systems in barrier areas

Drainage problems in irrigated areas generally occur where a barrier of heavy textured soil impedes the movement of excess irrigation water or seepage. There are two types of soil barriers which cause the water-table problems. The most spectacular type of barrier often encountered in the flat irrigated valleys of the West can best be described as a long transverse-subsurface dike or clay bar which lies at right angles to the general direction of subsurface seepage flow. The second and most common type of barrier is a layer or stratum of soil which underlies an entire area and prevents the natural release of ground water downward and out of the root zone of plant growth.

The soils of the Imperial Valley were built up as a part of the Colorado River Delta. During recent geological times the Colorado River flowed alternately into the Salton Sea, filling the basin, and into the Gulf of Lower California. It is assumed that each time the Colorado River filled the Salton Basin, sediments were deposited, offshore bars were formed, and lacustrine type of soil has resulted. Thus, the formational elements were present which were favorable to the deposition of both horizontal barriers of heavy textured soils and long transverse-clay dikes around the periphery of the present valley.

Most of the tile-drainage systems are along the northeast edge of the Valley. It is here that the most recent geological sedimentary deposits have been mantled by overwash of coarse soils. It is also in this general vicinity that the most revealing examples of the subsurface-clay dikes occur. For example, visualize the Salton Sink as it might have been during one of the geological periods when the Colorado River flowed into it. The water would have formed a huge lake in an area encompassing the present irrigated area. The eastern lakeshore would have been approximately at the boundary of the East Highline Canal. The various shorelines which may have formed as the lake receded might easily have produced the type of surface and subsurface configuration present today. Seepage from the East High Line Canal and from lesser branch canals, together with excess irrigation water, moves downslope to the west. When this excess ground water reaches a transverse-subsurface-clay dike or bar, it builds up behind this barrier. Eventually the water table is at or near the ground surface. Evaporation soon produces a saline area where crops will not grow. These areas are clearly indicated on aerial photographs as light colored streaks or strips. At, or down the slope from, these light areas the long transverse-clay dikes may be located at from 2 to 5 feet below ground surface.

Piezometer study. --A water-table investigation is generally made of these problem areas to locate the source and direction of flow of the underground seepage. Piezometric observation wells are usually placed at right angles to the clay barriers and in one or more lines crossing the barriers. When these data are plotted on profiles the drainage problem is instantly revealed. The magnitude of rise and fall of the water table due to irrigation and seepage can be charted.

Designing the tile-drainage system. --The most important single factor in the design of a tile-drainage system is the position of the laterals with respect to the transverse barrier. Excess seepage and irrigation water originating up slope from the barrier tends to build up at the barrier and forms a high water table. The

culation, an average tile spacing for the whole field is the result. By analyzing the soil borings, it is possible to increase the spacing in the lighter textured soil areas and decrease the spacing where there is reason to suspect that more tile would be advantageous. If piezometers indicate a definite source of seepage, the design provides for maximum drainage at the indicated point.

The final design takes into consideration all features which the reconnaissance and detailed surveys have revealed to be contributary to the problem. Some rules of design are as follows:

(a) Only one outlet is made for each 1/2-mile of district-owned open drain.

(b) Lateral lines are placed across the direction of flow of the underground water, if at all feasible.

(c) An open drain along any side of the property to be drained is considered a tile line, and the first designed line would thus be located one space distant from the open drain.

(d) Outlets are never located through rows of trees nor is a lateral line located adjacent to a windbreak. Tree roots will clog tile lines.

Size recommendations. --The following tile-size recommendations are used as a guide:

(a) Lateral lines should be at least 4 inches in diameter.

(b) The downstream diameter of any lateral line longer than 1,320 feet should be at least 5 inches.

(c) Collecting lines should not be less than 6 inches in diameter.

(d) The downstream portion of any collecting line at the point where the aggregate lineal feet of upstream lateral lines exceeds 15,000 feet should be at least 8 inches in diameter.

The foregoing tile-size recommendations are the minimum requirements for the Imperial Valley. It should be pointed out that there are several distinct advantages to using larger tile sizes. In view of the small difference in cost of 4-inch, 5-inch, and 6-inch tile, the advantages of larger sizes often outweigh the added cost. Larger sizes will, of course, carry greater volumes of flow. This factor is important when leaching becomes a part of the reclamation. Larger sizes also require less exacting excavation standards. This factor is important where grades are flat. Larger sizes are less likely to silt up, thus cutting maintenance costs.

Drainage systems in barrier areas

Drainage problems in irrigated areas generally occur where a barrier of heavy textured soil impedes the movement of excess irrigation water or seepage. There are two types of soil barriers which cause the water-table problems. The most spectacular type of barrier often encountered in the flat irrigated valleys of the West can best be described as a long transverse-subsurface dike or clay bar which lies at right angles to the general direction of subsurface seepage flow. The second and most common type of barrier is a layer or stratum of soil which underlies an entire area and prevents the natural release of ground water downward and out of the root zone of plant growth.

The soils of the Imperial Valley were built up as a part of the Colorado River Delta. During recent geological times the Colorado River flowed alternately into the Salton Sea, filling the basin, and into the Gulf of Lower California. It is assumed that each time the Colorado River filled the Salton Basin, sediments were deposited, offshore bars were formed, and lacustrine type of soil has resulted. Thus, the formational elements were present which were favorable to the deposition of both horizontal barriers of heavy textured soils and long transverse-clay dikes around the periphery of the present valley.

Most of the tile-drainage systems are along the northeast edge of the Valley. It is here that the most recent geological sedimentary deposits have been mantled by overwash of coarse soils. It is also in this general vicinity that the most revealing examples of the subsurface-clay dikes occur. For example, visualize the Salton Sink as it might have been during one of the geological periods when the Colorado River flowed into it. The water would have formed a huge lake in an area encompassing the present irrigated area. The eastern lakeshore would have been approximately at the boundary of the East Highline Canal. The various shorelines which may have formed as the lake receded might easily have produced the type of surface and subsurface configuration present today. Seepage from the East High Line Canal and from lesser branch canals, together with excess irrigation water, moves downslope to the west. When this excess ground water reaches a transverse-subsurface-clay dike or bar, it builds up behind this barrier. Eventually the water table is at or near the ground surface. Evaporation soon produces a saline area where crops will not grow. These areas are clearly indicated on aerial photographs as light colored streaks or strips. At, or down the slope from, these light areas the long transverse-clay dikes may be located at from 2 to 5 feet below ground surface.

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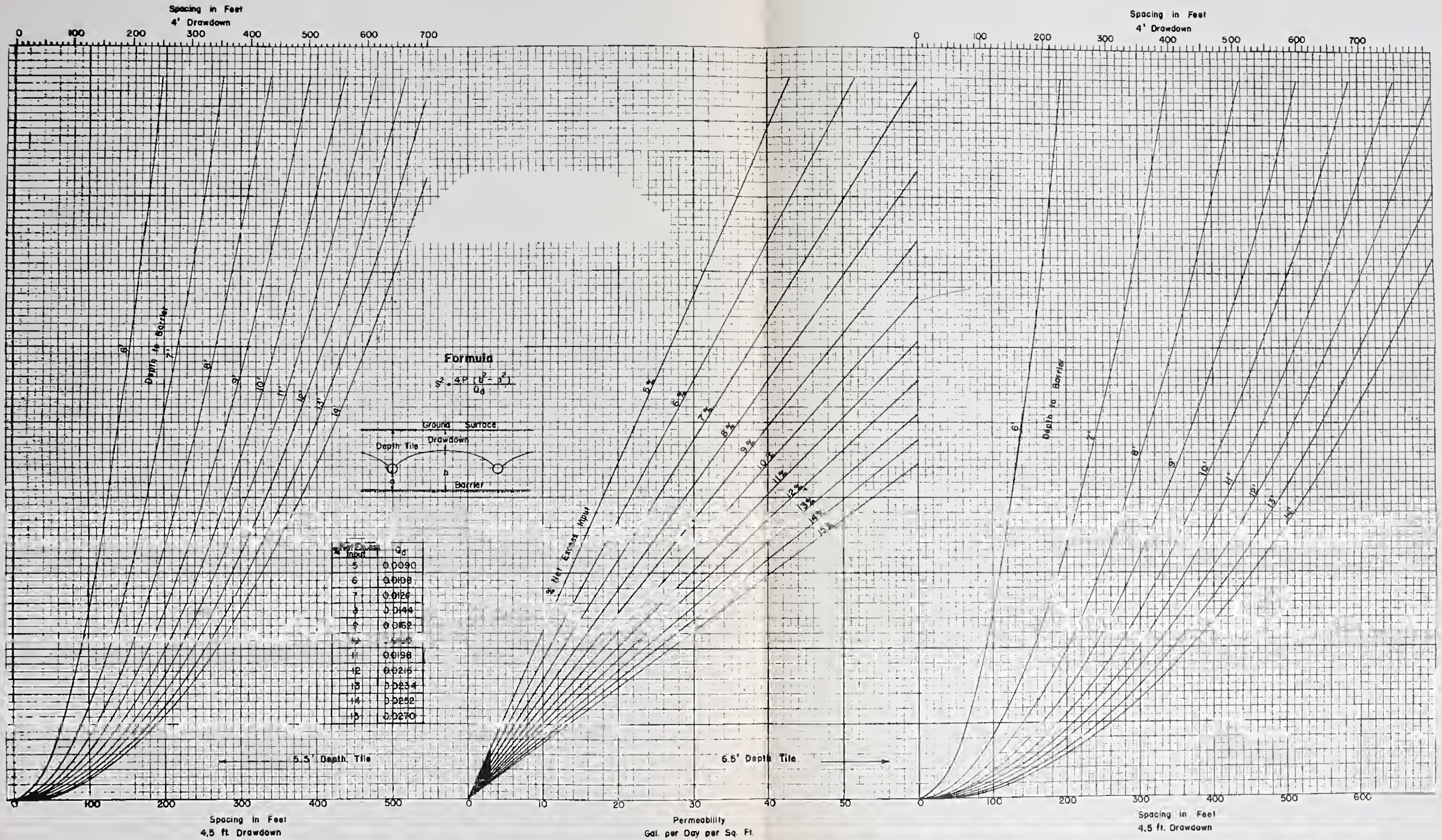

Figure 16.--Tile-spacing curves

first drainage lateral should be placed as close as possible to the upstream face of the barrier and should run parallel to it. The lateral should be in the aquifer or sandy material, but very near the heavier clay barrier that extends towards the ground surface. Additional lines up slope from the key lateral are installed at a spacing dictated by a consideration of soil permeability, water-table datum, and surface-crop conditions. A minimum of two lines should always be recommended in any barrier-drainage system unless the aquifer area between the barrier mounds is extremely narrow. The lines recommended should have an azimuth closely paralleling the alinement of the dikes or mounds. In several cases the key line has been located and staked in the field. Auger borings are made prior to finally locating the key lateral to be sure it will not be placed in the heavier soil.

Figure 17 is a profile over 2 parcels of land which have been investigated for drainage. Soil borings, piezometer observation wells, and onsite inspection revealed the locations of the clay mounds. Figure 17 also shows the location of the tile-drainage laterals and the resultant lowering of the water table. These two farms are now approaching about 90 percent of normal productivity after 4 years. A more rapid return to normal production would have resulted if these test farms had been leached, or flushed, to remove the excess salts.

Horizontal or undulating barrier problems. -- Where the impervious clay strata lay horizontally, as in old lake-bed deposits, the problem of drainage design is somewhat different from that on a transverse-barrier problem. In Imperial Valley, during the geological past, the Valley was inundated and lay dry for many different alternate periods. During the dry times sand dunes may have formed and moved over the valley floor. These were later covered by water and clay deposits of varying thickness. Hence the clay layers are undulating in character and may vary in their depth considerably in as small an area as one field. This phenomenon has been observed many times and has been depicted graphically by logging soil borings and plotting profiles and contour maps of the clay layers. Borings are made from 9 to 12 feet in depth with soil augers. Usually borings are made in a grid, the spacing of holes depending on the complexity of the soil strata (an average of about 6 holes are bored on each 40-acre parcel). The log sheets of the holes are used to plot a contour map of the top surface of the barrier layer. If the surface of the clay layer is at a depth of 5-1/2 to 10 feet, an ordinary grid system of tile lines spaced according to a tile-spacing formula is used. However, if this top surface is from 3 to 6 feet below ground surface, the tile lines are located so as to avoid being placed in the clay. Experimental studies have shown that drainage to the tile line from the midpoint between lines may be greatly reduced by imbedding the tiles in the clay. The most advantageous location for drainage is 6 inches or more above the clay. In the semi-shallow horizontal clay barriers encountered in the Imperial Valley, depth of tile lines is always a problem. The balance between placing a line 6 inches deeper or keeping it 6 inches shallower to avoid imbedding in clay is in favor of a shallower tile placed in the sandy soil. The tile systems in these shallow barrier areas need not follow a rigid "square-with-the-world" alinement. They may angle off or even have some curves, although it is difficult to get the tile contractors to install this type of system. The secret then of securing a good design on a horizontal barrier area is to have a good contour map of the top face or the underground clay layer. Using this as a guide, the tile system is designed primarily to traverse down the valleys and swales in the clay barrier. The important factor in the barrier type of drainage system is that the productive lines are the ones laid in the aquifer.

Interceptor drains

Single lines of tile which are installed along canals and laterals or below benchland are called interceptor lines.

Interceptor lines are designed to collect seepage water. This seepage usually flows in one or more definite strata. To be effective, the tile line should be placed in the stratum through which the seepage is flowing. The depth to and location of these water-bearing strata thus dictate the depth of the interceptor lines.

Too often the interceptor line is placed deep for the dual purpose of interception and ordinary lateral drainage of the adjacent field. In heterogeneous soils this may be successful, but where a barrier stratum is located between the aquifer and the tile, little, if any, seepage water will get into the tile.

Tile-installation progress

The installation of tile lines in the Imperial Valley has progressed to the point where over 200 miles of tile lines are installed in the Valley each year. Both clay tile and concrete tile have been used. About 50 percent of the tile used in the last few years is of concrete (table 14). Also in table 14 is a calculation of the total amount of salts removed from the Valley by the drainage system. To produce the figures shown in column 4, the total amount of salts being imported into the Valley has been equated to the total amount of salts being moved into Salton Sea. The year 1949 was the first year since these data have been compiled in which more salts were being removed from the Valley than were being brought in. It is estimated that about one-fourth of the Valley has now been tiled (fig. 18). Under present conditions, twice as much tile as has been installed could be used with profitable results in the irrigated areas of the Valley.

Over 100 tile systems have been designed by Soil Conservation Service--Operations in the

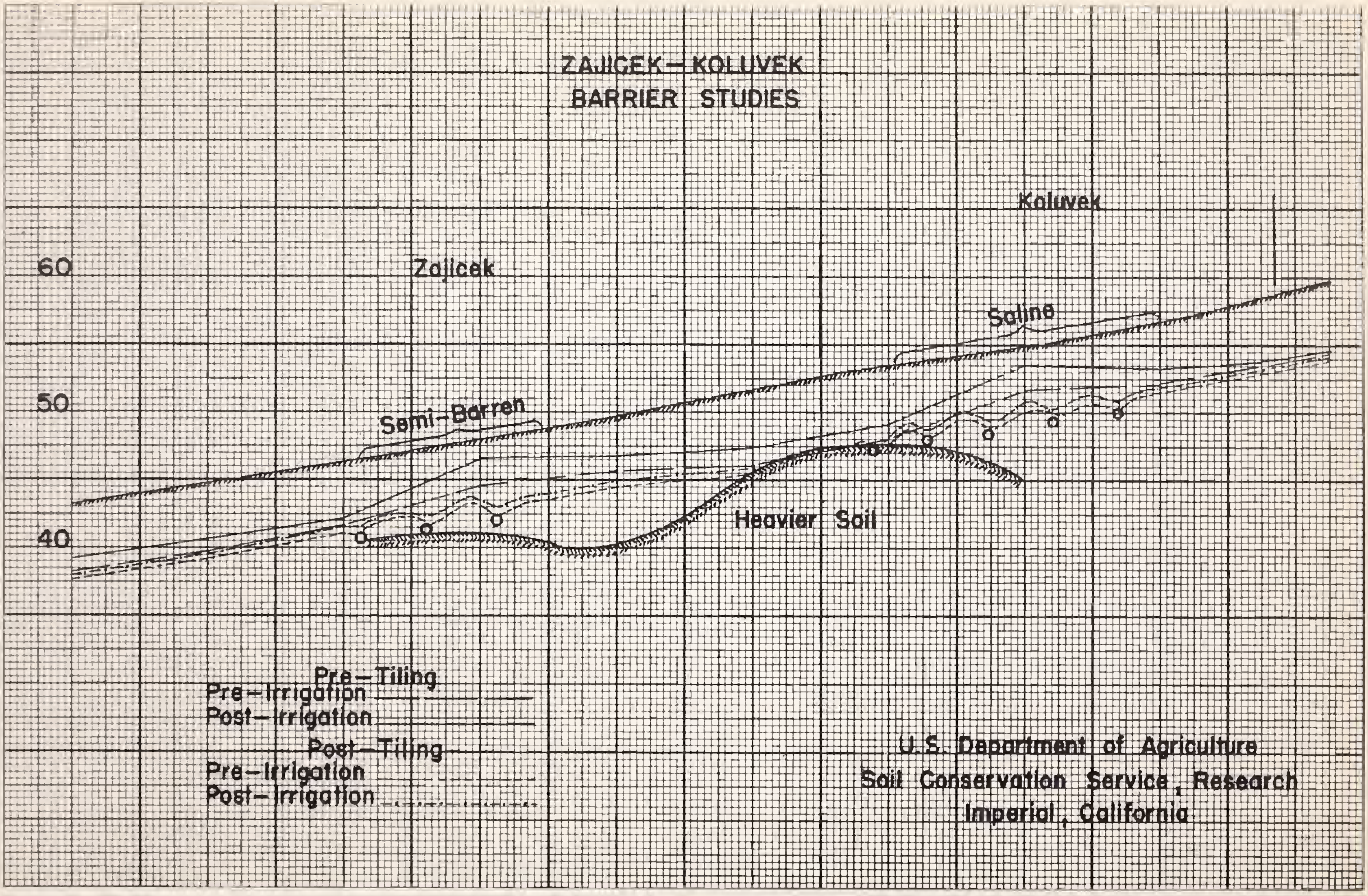

Figure 17.--Profile over two parcels of land which have been investigated for drainage and location of the tile-drainage laterals and resultant lowering of the water table, Imperial Valley, Calif.

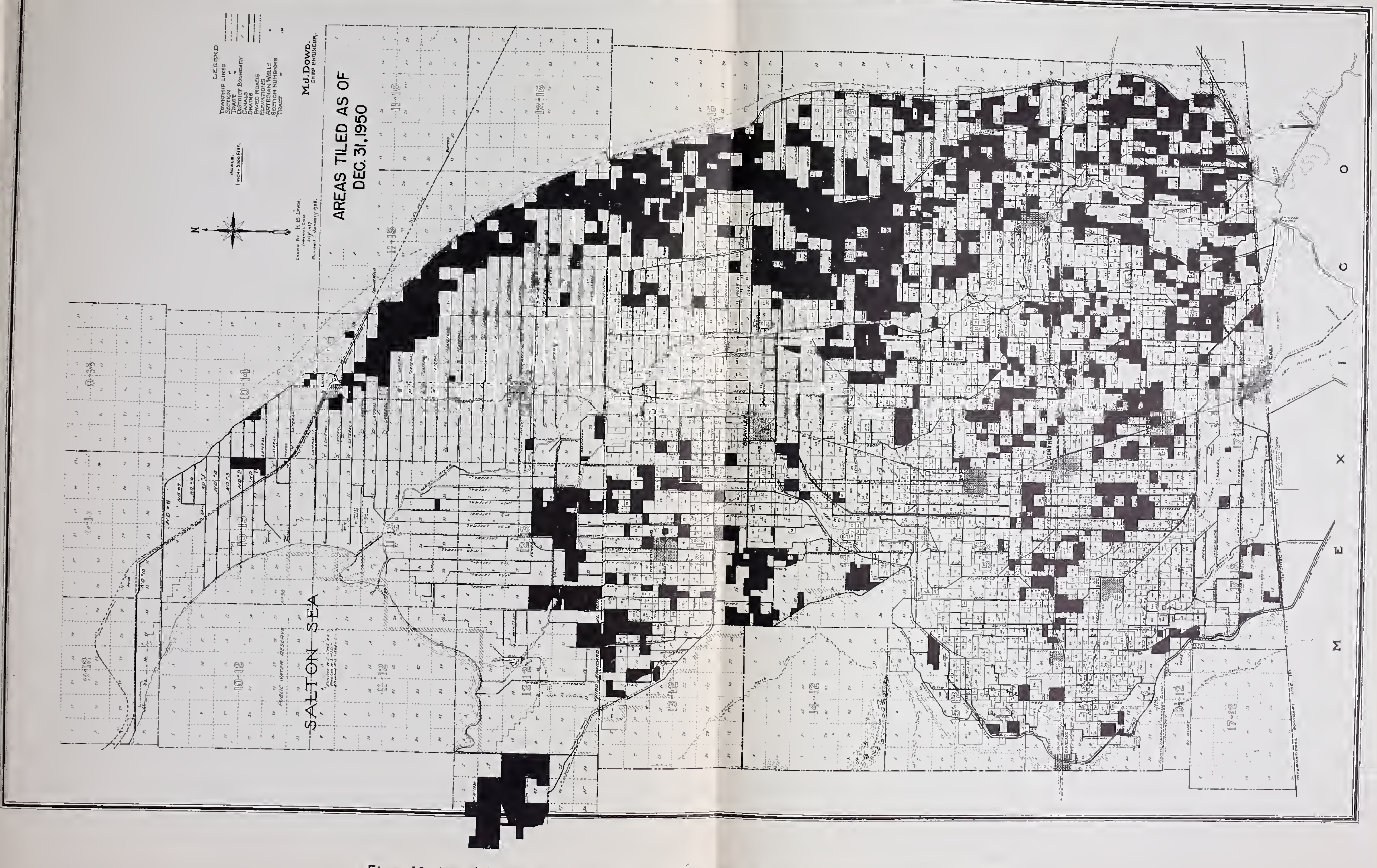

Figure 18.--Map of the Imperial Irrigation District, Calif., showing the areas tiled as of December 31, 1950.

Imperial Valley, using the techniques outlined above and utilizing the tile-spacing formula to determine tile spacing. With very few exceptions, these systems are considered to be an outstanding success. The soil conservation district has a backlog of over 100 applications for assistance by farm owners who have drainage problems.

TABLE 14.--Tile installation and salt balance in the Imperial Valley, Calif., 1929-49

Year	Tile installation			Dissolved solids, drainage output as percent of diversion input
	Per year		Total	
	Miles	Acres	Acres	
1929	5.56	328	328	
1930	11.97	606	934	
1931	2.69	159	1,193	
1932	2.30	136	1,329	
1933	24.03	1,418	2,747	
1934	3.52	208	2,955	
1935	3.49	206	3,161	
1936	20.01	1,181	4,342	
1937	33.65	1,985	6,327	
1938	129.59	7,646	13,973	
1939	95.96	5,662	19,635	
1940	66.84	3,944	23,579	
1941	46.08	2,719	26,298	
1942	37.15	2,191	28,489	
1943	53.24	3,141	31,630	92.59
1944	54.47	3,214	34,844	87.80
1945	55.40	3,269	38,113	93.64
1946	133.00	7,847	45,960	82.41
1947	325.00	19,190	65,150	87.19
1948	394.00	17,220	82,370	95.86
1949	456.00	21,670	104,040	105.30
Mean or total	1,953.95	104,040		92.11

TABLE 15.--Summary of data on tile-spacing checks of drainage systems in Imperial Valley, Calif.

Farm	Acres	Type system	Designed water-table depth	Designed spacing	Installed spacing	Approximate average water table after tile
				Feet	*Feet*	*Feet*
O'Dwyer-Metz	160	Grid	4.5	150-250	150-250	4.5
V. K. Rood	160	Grid	4.0	200	200	4.0 +
U. of California	80	Grid	4.5	--	--	--
H. B. Ross	320	Grid	4.5	260	300	4.0
James Simons	310	Grid	4.0	195	195	4.0 +
Higgins and Keller	620	Grid	4.0	200	200-400	4-3
Struikman	160	Grid	4.5	250	350	3
K. Koluvek	60	Barrier	4.5	175	175	4.5 +
J. Zajicek	120	Barrier	4.5	200	200	4.5
John Suchy	20	Barrier	4.5	200	200	4.5
A. Immel	240	Grid	4.5	190	250	3-4
John Suchy	160	Barrier	4.5	200	200	4.5
W. B. Collins	160	Grid	4.5	300	400	3.5
F. Jurn	160	Barrier	4.5	200	200	4.5 -
R. B. Wilson	300	Grid	4.5	250	350	3.5
S. Dean	40	Barrier	4.5	225	225	4.5 +
J. C. Horton	50	Grid	4.5	275	275	4.5
M. Chalupnik	80	Grid	4.5	275	275	4.5
U. of California	80	Grid	4.5	300	300	4.0

Tests of Tile Systems

Extensive tests of designed and installed tile systems were made through the combined cooperative work of Soil Conservation Service--Operations and Research. These tests were conducted to determine whether the techniques and procedures proposed have produced the desired results on the various individual drainage problems.

Procedure

In making a check on an installed tile system, the procedure is as follows: (1) Piezometers are located adjacent to and out from several of the most representative lines in the grid system; (2) measurements are made of the flow from the tile line; and (3) observations are taken through one or two irrigation cycles. These observations consist of (a) water-table depths with piezometer-observations wells; (b) outflow from the tile system (which is prorated to outflow per foot of tile); and (c) estimates of the amount of water applied and wasted to determine approximate input of irrigation water. These data not only reveal whether the tile system is functioning according to design, but also reveal whether the basic assumptions made in developing and using the spacing formula are correct.

Over 19 tile systems have been tested using this procedure (table 15). It is to be noted that the designed water tables have been attained in a majority of the systems checked.

Flow from tile lines

In an attempt to make checks of the amount of water flowing from the drains, data have been compiled from flow charts and other spot checks of flow from tile outlets. These tests were to determine, if possible, what percentage of the amount of water applied reached the tile system and was eventually carried away from the area. Table 16 is a summary of these data. Analysis

TABLE 16.--Summary of data on flow from tile lines, Imperial Valley, Calif.

Location of plot	Period	Input water applied to plot	Outlet drainage from tile system		Remarks
		Acre-feet	*Acre-feet*	*Percent*	
Meloland Home Plot.............	1943	65.97	4.54	6.9	Irrigation
Meloland Home Plot.............	1944	87.56	16.69	19.0	Leach no Waste
Meloland Home Plot.............	1947	76.38	6.21	8.1	Irrigation
Meloland Home Plot.............	1948 Jan.--June	23.48	2.41	9.4	Irrigation
Jim Bridger....................	1942	161.5	14.9	9.2	Irrigation
Tony Homola....................	1 Irrigating cycle	6.1	.49	8.0	Irrigation
O'Dwyer--Mets..................	80-day leaching	77.0	25.4	33.1	Leaching
Martin Wahl....................	150 days	143.2	12.7	8.9	Irrigation
R. B. Wilson...................	30 days leaching	[1] 125.4	14.1	11.1	Leaching
R. B. Wilson...................	44 days leaching	[1] 170.2	13.8	8.1	Leaching
R. B. Wilson...................	74 days leaching	[1] 273.7	24.6	9.0	Leaching
R. B. Wilson...................	48 days leaching	[1] 81	14.9	18.4	Leaching
R. B. Wilson...................	136 days leaching	[1] 630	45.2	7.2	Leaching
R. B. Wilson...................					Irrigation
Koluvek 13-16 Sec. 6...........	15-day cycle	4.0	1.37	34.2	Irrigation
Zajicek 13-16 Sec. 6...........	23-day cycle	30.1	.83	2.8	Irrigation
Suchy 13-16....................	12-day cycle	19.8	2.65	13.4	Irrigation
Metz 14-15 Sec. 8..............	16-day cycle	68.5	6.8	9.9	Irrigation
Wright 12-13 Sec. 26					
Plot 1.........................	11-day cycle	12.5	.62	5.0	Irrigation
Plot 2.........................	11-day cycle	20.0	1.27	6.4	Irrigation
Plot 3.........................	24-day cycle	20.9	1.25	6.0	Irrigation
Plot 4.........................	24-day cycle	20.9	1.25	6.0	Irrigation
Plot 5.........................	13-day cycle	19.7	.62	3.2	Irrigation
Sperry 12-13 Sec. 27					
Plot 1.........................	19-day cycle	28.5	17.37		Irrigation
Plot 2.........................	19-day cycle	28.5	17.37		Irrigation
Plot 3.........................	16-day cycle	14.7	1.11	7.6	Irrigation
Plot 4.........................	16-day cycle	16.0	.80	5.0	Irrigation
Plot 5.........................	19-day cycle	60.3	9.49	15.7	Irrigation
Suchy 13-16 Sec. 5-6...........................	18-day cycle	99.6	12.40	12.4	Irrigation
Chalupnick 14-15 Tr. 64 and 84................	18-day cycle	56.2	5.71	10.2	Irrigation

[1] Surface waste subtracted.

would seem to indicate that during normal irrigation a little less than 10 percent of the amount of water applied drains out through the tile systems. This figure appears to substantiate the 10-percent theory in estimating Q, the amount of water to be drained in designing tile systems.

A comparison has been made between the prorated permeabilities of the various plots tiled and the percentage of outlet-drainage flow in the tile systems. It has been found that a rough correlation exists between permeability and percent flow. The more permeable soils trend toward a larger percentage of flow. Thus, a tile system installed in a field having an overall permeability of, for example, 1 inch per hour (±15 gallons per square foot per day) would tend to produce only about 5 percent of the amount of water applied. A tile system installed in soils having a permeability of 2 inches per hour (±30 gallons per square foot per day) would tend to produce about 10 percent of the amount of water applied. A tile system installed in soils having a permeability of 3 inches per hour (±45 gallons per foot per day) would tend to produce about 15 percent of the amount of water applied.

Increased production from tile systems

Perhaps the most valid check of an installed tile system is whether there is any increase in production of crops after tiling. Spot checks have been made on a number of tile systems. Most of the land was leached after tiling. The following tabulation is a compilation of data from these spot checks, showing increased production as the result of tiling and leaching:

Farm	Crop production prior to drainage	Crop production after drainage
N. Correll	Abandoned	Alfalfa, 9 tons per acre
O'Dwyer-Metz	Poor alfalfa	Sugar beets, 16 tons per acre
H. B. Ross	Barley, 2,200 lbs. per acre	Barley, 4,600 lbs. per acre
H. B. Ross	Flax, 1,120 lbs. per acre	Flax, 1,624 lbs. per acre
A. Immel	Saline bareland	Barley, 2,227 lbs. per acre
J. Zajicek	Bare spots in field	Good production on entire field
Ward Casey	Wheat, 24 bu. per acre	Wheat, 66 bu. per acre
John Suchy	10 acres no production	1 acre, no production
University of California	Bare spots	Uniform germination

Tile-Flow Measuring Devices

The program of testing tile systems and getting a large number of flow measurements involves a great deal of time and effort. There are several methods of measuring the discharge or free flow from farm tile-line outlets. A simple method of getting instantaneous flow records is by bucket and stopwatch. This method is accurate but is feasible only for low flows.

The most commonly used means of recording discharge from a tile outlet is with a stilling box, V-notch weir, and water-stage recorder. The V-notch-weir will give good results if properly installed and correctly operated. This device has certain drawbacks, however. It cannot be moved about easily and thus does not lend itself to wide-scope operations. In most areas, unless the box is covered and screened from sunlight, the notch is quickly fouled by moss and aquatic growth. Then, too, it requires a head loss, which is seldom found at the outlet of a tile system in irrigated areas.

In the Imperial Valley research work, both instantaneous flow data and a record of the regimen of flow over short periods of time are needed in analyzing the efficiency of installed tile systems. Hence, investigations were made in an attempt to:

(1) Calibrate a device for getting approximate, instantaneous flows from 4-inch, 6-inch, and 8-inch tile outlets under normal conditions.

(2) Build a portable device for recording flows from tile outlets through irrigation cycles or for short periods of time.

To accomplish this, the project has adapted two flow devices to these drainage studies. One device is called the tile-effluent measuring stick; the other is the continuous flow recorder.

The tile-effluent measuring stick

The tile-effluent measuring stick, devised for getting instantaneous flow measurements from tile outlets, is patterned after the Clausen-Pierce Weir Gage (9) used to measure the flow over free-flowing and submerged weirs. Similar devices have previously been developed to measure hydraulic flow. One such was used by Hayden (7) to record flows in narrow canals. J. B. Lippincott (12) also perfected a similar measuring stick.

All these devices embodied the principle that velocity head could be measured within reasonable limits and that a measuring rule, held vertically in the stream, could be calibrated to give fairly close readings of the volume of flow.

The tile stick or outlet-measuring rule used in the Imperial Valley works on the same principle as the above devices. When the stick is held vertically on the outlet lip of the tile line, the velocity of approach is converted to velocity head. This velocity head is manifested in a jump or pip on the upstream edge of the stick and is easily measurable. The velocity head records to an extraordinary degree of accuracy within certain limits of outlet slope. Depending on the

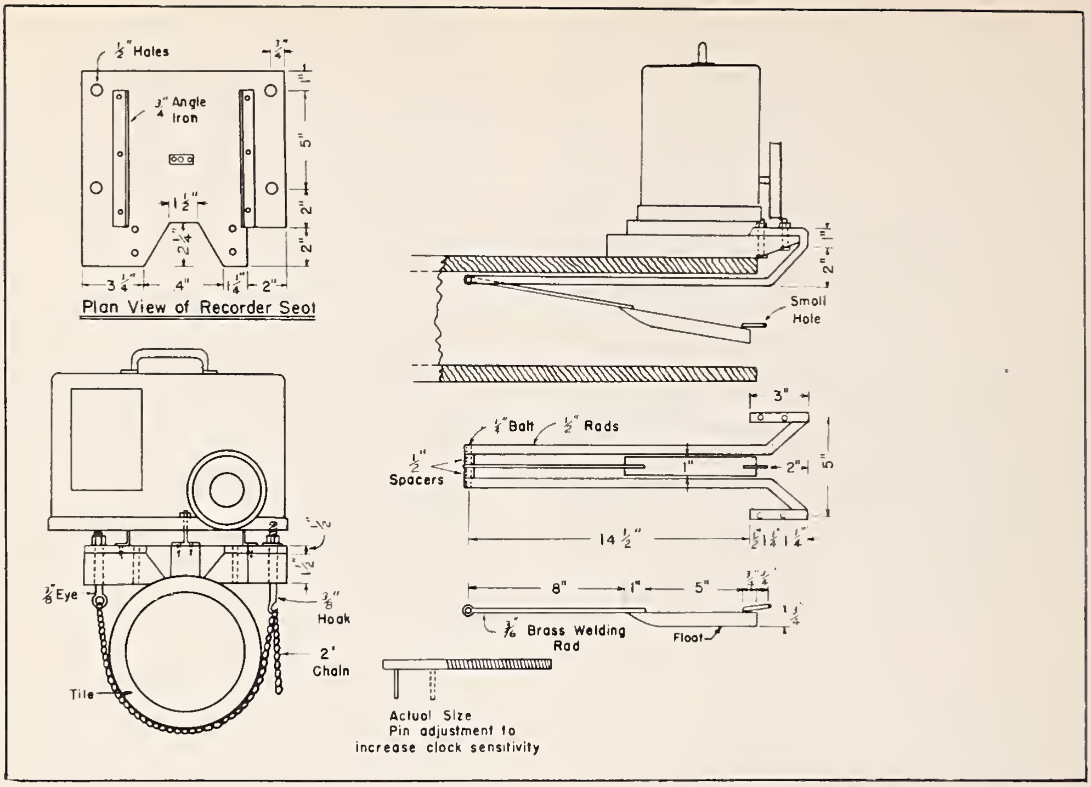

Figure 19.--Tile effluent recorder

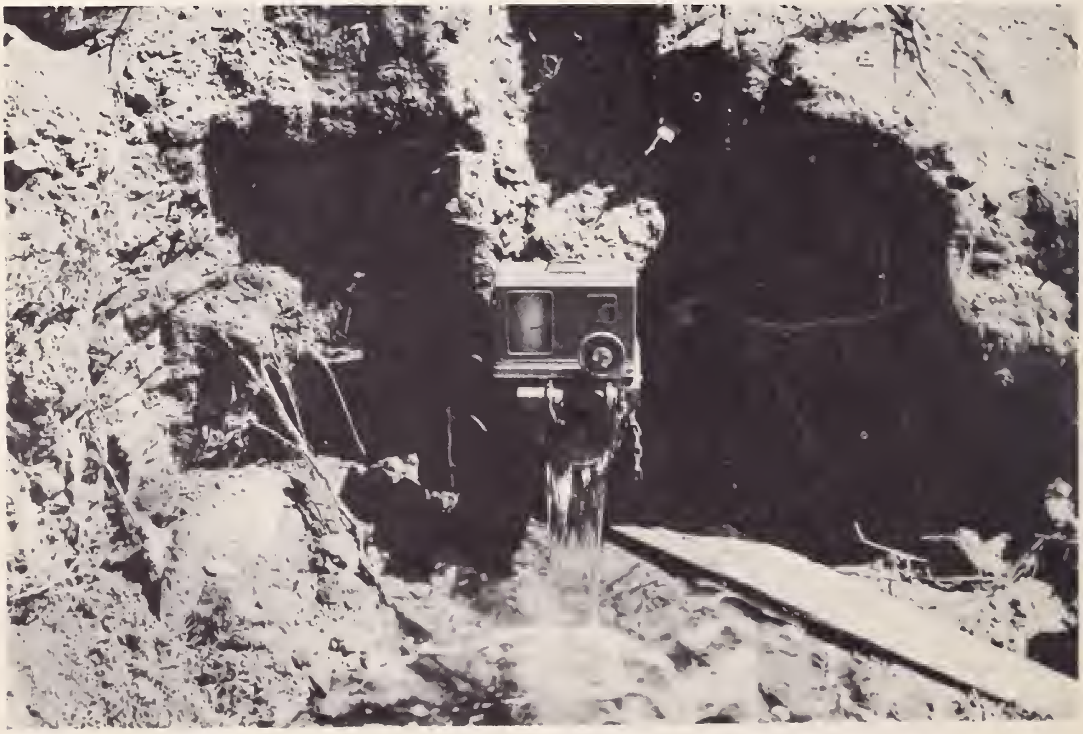

Figure 20.--Typical field installation of continuous flow recorder.

size of tile, the recording stick has been used to record flows ranging from 2 gallons per minute in the 4-inch outlet, to 530 gallons per minute in the 8-inch tile.

To make a reading on a tile outlet, the stick is inserted in the lip of the tile with the knife edge against the flow. This gives a depth-of-flow measurement. The tile stick is then thoroughly wetted and inserted in the lip of the tile with the narrow edge against the flow. The top of the velocity-head pip which climbs the stick is read and recorded. A third reading can be made by inserting the flat side of the tile stick in the lip to record velocity head. In making a flat-side reading, best results are obtained by using a dry, absorbent wooden tile stick. The stick is slowly lowered into the flow from above until it touches the bottom lip of the tile and is then slowly removed. The high-water mark made by the velocity head gives a reading comparable to the narrow-edge pip reading. In inaccessible outlets, this type of reading is sometimes the only one obtainable. In making field observations, a small pocket mirror is very useful to read the scale on the tile stick.

The various sizes of tile outlets, 4-inch, 6-inch, and 8-inch, have been calibrated for various depth and velocity-head measurements made with the dip stick. Thus, by making a dip measurement and reading from the chart, the approximate flow can be estimated.

The flow recorder

Previous work.--Many types of flow recorders are being used to clock a continuous record of pipe or tile outflow. J. E. Christiansen (2) outlines a number of different devices for use in measuring hydraulic flow, some of which are adaptable to tile-outlet measurement. Rohwer's bulletin (14) on measuring pipe discharge outlines methods which might be adapted to the recording of large flows. The Simplex Valve and Meter Company (16) has placed on the market what it calls a "Type S, Parabolic Flume" for measuring open flow of water, sewage, and industrial liquids. This device appears to be adaptable to tile-outlet measurement and under rigid installation standards might be ideal for use in getting tile-effluent flow records.

In the drainage-research work in the Imperial Valley it was determined that the need was for an easily installed, portable device, which could be placed at the mouth of a tile outlet and left to record flows for a period of several weeks. While accuracy of readings and close determination of volume of flow are of value in analyzing tile-system efficiency, the most important single factor is felt to be the rate of change during irrigation cycles. Thus, some of the characteristics of accurate measurement are sacrificed to the main objective; for example, fluctuation of flow.

Recorder apparatus.--The continuous flow recorder consists of a standard Friez Model F-W water-stage recorder mounted on a platform which can be fixed to a tile-outlet pipe (fig. 19). Bolted to the platform are two 1/2-inch rods which are bent out over the upper crown of the tile outlet and around 180 degrees back up into the roof of the outlet. Suspended between these rods is a light brass arm which has free vertical movement from a pin connection at the ends of the rods. Affixed to the free end of this arm is a lightweight float which rides on the crest of the flow at the lip of the tile outlet. The recorder is mounted on the wooden platform in such a way that the recorder wheel is out from and over the edge of the tile outlet and in line with the small eyelet hole on top of the float. The float is suspended over the recorder wheel by a flexible linen cord with a very small counterbalance weight.

An essential feature of the apparatus is its sensitivity and general lightness in weight. The float is made of brass shim stock 0.0001 inch thick. The float arm is made of 3/16-inch brass welding rod. The combined arm and float weights about 84 grams. The counterbalance weight for this size float is 44 grams. The downstream end of the float is left open to prevent waterlogging in case of leaks in the float. Another essential precaution is to make the bent rods which curve back into the tile and the float arm itself as long as possible. The longer this float arm the more nearly vertical is the arc of the float as the flow increases or diminishes. Figure 19 shows how the device fits on the outlet of the tile. The circular arch notched into the base of the wooden platform is made large enough so that the device can be attached to 4-inch, 6-inch, or 8-inch pipe outlets.

Method of installation.--In making a field installation, it is usually necessary to dig the soil away from the projecting end of the tile outlet. A minimum of 8 inches of projection will serve to mount the apparatus (fig. 20). The wooden platform, with bent rods, float arm, and float attached, should be set level and chained tightly to the outlet. The recorder is then placed in position on the wooden platform and bolted securely. In hooking up the float and counterbalance weight, one complete loop is made around the recorder wheel to prevent "slip" of the linen cord. The float is then depressed by hand until it rests on the bottom inside lip of the tile, and the recorder wheel is slipped around, setting the recorder pen at zero. Then as the float rises on the crest of the water, the depth is recorded by the pen.

On an FW-1 water-stage recorder the pen will travel one-half inch for each inch the float rises or falls. In order to increase the traverse of the pen, the pin in the clock-arm mechanism was changed to a new position (fig. 19). This increased the traverse of the pen arm to a 1-to-1 ratio.

The flow recorder has been calibrated for the Imperial Valley tile-outlet conditions. It is not difficult to make a calibration for any individual tile outlet. By utilizing a stopwatch and bucket, a few different volumes of flow can be measured for the various depths of flow as recorded on the flow chart. From these points, a ratio between depth and volume can be established for the individual tile outlet.

The continuous flow recorder has been used to secure data on:

1. Maximum and minimum discharge and duration of high and low flow.
2. Trend of change in tile discharge.
3. Time lag between irrigation and increased flow.
4. Diurnal fluctuation of flow.
5. Disclosure of leaks or breaks in lateral lines.
6. Detection of source of seepage.

It is doubtful whether the many tile-system checks and leaching work could have been accomplished without these two flow-measuring devices.

Leaching Studies

For the past few years, the Research staff has been carrying on various types of leaching studies. While the main effort has been directed toward development of tools and methods for investigation and design of drainage systems, the reclamation of these soils has also been part of the overall research work. In 1943, some laboratory-leaching studies were attempted using soils brought in from the Meloland Farm.[29] These studies indicated that only a relatively small amount of water was required to pass through the soil profile to remove a large percentage of the saline elements.

In 1946, with the tremendous increase in the installation of the lines in the Imperial Valley, there was a correspondingly great increase in the acreage of land being leached.

The practice in the Imperial Valley is to build contour borders in the fields and pond water to a depth of 9 to 18 inches for periods ranging from 30 days to 6 months or more. This has been successful in most instances and is today the accepted method of reclaiming land. The questions raised by these practices were:

(1) How long should the water be ponded on the various textured soils?

(2) What are the best methods to use, keeping in mind that water should be conserved?

(3) What are the costs and benefits of leaching?

Determination of these factors was the objectives of our subsequent leaching-research program. The studies which were carried on were conducted as the opportunity presented itself. Except for a few laboratory experiments and the Meloland Farm study, all the work was done on privately owned land where the control over physical factors could not always be maintained.

Leaching theories

Several theories on leaching have been proposed which, it is felt, should be open for discussion. These theories are as follows:

(1) When water is ponded over an area that has been tiled, there is more water flowing to the tile lines from areas adjacent to the lines than from points midway between laterals.

(2) When the ponded leaching water is removed, the ground-water table allowed to recede, and a drawdown curve obtained by the tile lines, the flow into the tile lines originates from all portions of the field. As the drawdown curve falls, more of the flow originates near the midpoint between laterals.

(3) When leaching is practiced by long periods of ponding, tile lines may become overloaded and back pressures may occur in the downstream reaches. In some extreme cases, impregnation by saline elements may occur at these points.

(4) When water is ponded, the surface soil in leaching plots tends to deflocculate and segregate during a leaching period. In heavy soils, this becomes quite a problem with respect to infiltration.

(5) When water is ponded, salt may be added to the soil by the leaching water. Enough leaching water should be wasted during leaching of heavy soils to maintain the salt balance in the leaching water.

(6) Leaching water will absorb or pick up some salt from the soil surface, and on slowly permeable soils the salt removal by the surface waste will approach that removed by the tile-drainage system.

(7) Saline elements are removed from the surface soils to depths of 20 feet or more during leaching periods.

(8) Longer leaching periods are required in heavy soils to remove the salts to deeper depths.

Analysis of theories

When examination is made of theory 1, some interesting phenomena are projected. Consider a hypothetical case: Water is ponded on the surface of the land which is drained by tile lines spaced an S distance apart. If the soil is homogeneous throughout and there is no barrier, a drawdown curve will develop. If the tile lines are flowing full and there is no back pressure on the lines, the amount of flow in the laterals will originate in about the following proportions: About 50 percent of the flow will originate in the space $S/8$ on each side of the tile lines, and the land on each side of the midpoint between tile lines will each produce only about 5 percent of the flow. This theory, in principle, has been proved mathematically by Kirkham (10).

The hypothetical case presented, wherein the soil is homogeneous and there is no barrier to restrict streamline flow to the tile lines, is one that seldom exists in the field. When recognition is made of the probable presence of a barrier below the tile lines, the flow from the midpoint becomes even less.

Theory 2 presents a diametrically opposite phenomenon. When ponded water is allowed to recede and a drawdown curve actually occurs about a tile line, the flow to the tile line approaches equality from all the area between the tile lines.

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[29] See footnote 5, p. 2

As the pond disappears, the water in the soil over the tile line flows away producing a drawdown curve. When the curve falls to lower levels, the water originates all along the drawdown curve. If an equilibrium curve occurs, all the flow is originating near the midpoint between tile lines. This theory is important in that it suggests a procedure for leaching which would result in an equitable removal of saline and alkaline elements.

Theory 3, concerning the presence of back pressure in drainage systems during leaching periods, deals with a critical factor in some soils. Back pressures have been observed in tile-drainage systems during the time leaching was in progress. These pressures generally occur where the collecting or baseline is underdesigned in size. They occur only during the leaching period and are usually not evident during ordinary irrigations.

Theory 4 has some basis of fact, since there is evidence of deflocculation and segregation on practically all leaching dikes. Areas having fine-textured soils show the greatest effect while soils of light texture show only a trace on the surface. Fine-textured soils may have a deflocculated layer 2 inches thick and about one-fifth the permeability of the soil immediately below it. The effect of this impervious layer can be minimized by shorter leaching periods and by disturbing the surface with disks and chisels between leaching periods.

In the fine-textured soils, theory 5 has a greater significance. On soils having a very low permeability, evaporation from the ponds makes the leaching water relatively saline. Sufficient water should be run through the ponds so that the leaching water maintains a low saline concentration and is thus able to absorb more of the saline elements in the soil.

Theory 6 suggests that leaching water will absorb or pick up considerable salt from the soil surface if it is kept relatively fresh in the leaching ponds. It is necessary to waste considerable water in order to maintain fresh water in the ponds. This waste water will absorb saline elements from the soil surface and carry them away from the area being leached.

It has been found from theory 7 that saline elements have been driven to depths greater than 20 feet during leaching runs. This phenomenon is of considerable value in reclaiming fine-textured saline soils. It has been observed that initially the salts are carried down below the root zone to depths considerably below the tile depth. It seems logical to assume that much of this salt will be removed by the tile system over a long period of time as it slowly moves back up to the surface.

Theory 8 maintains that saline elements are driven to deeper depths by longer rather than shorter leaching periods. A leaching period of 100 days would remove a greater amount of salt to 20 feet than four 25-day periods. This is due to the lag in time between when the leaching water is applied and when the water table reaches a height sufficient to drive the salts down. It may require 40 days for the water table to reach this point in some soils. Consequently, by the time this point is reached the pond is dried up and little if any deep movement of salt results.

Experimental leaching procedure

Experimental plots were selected at widely separated locations over the Valley. The salt balance in the plots ranged from medium to highly saline concentrations, and the soils ranged from moderately to slowly permeable. More emphasis and study was given to fine-textured slowly permeable soils since they are the most difficult to drain and reclaim.

The sites selected were on farms where extensive soil borings had been made so that the various strata could be classified. For the most part, the tile drainage on the tracts studied had been designed by the Soil Conservation Service. No soil amendments such as lime, sulphur, or gypsum were used in any of the field experiments. Ponding periods ranged from 30 days to an extreme of 136 days on one plot. The water applied was measured by the standard Imperial Irrigation District type submerged orifice gates. In some of the later studies, wooden Parshall flumes were installed for measuring water applied and water wasted. Tile flow was measured using V-notch weirs or Bradshaw-type flow recorders. On one plot (Wilson), an evaporation pan was installed and readings taken to record losses due to evaporation.

The soil sampling was done prior to leaching and at intervals during leaching cycles. The 5-foot depth samples were taken with a modified King-type coring tube. The 20-foot depth samples were taken with a posthole auger.

Most of the chemical analyses, both for the waters and the soils, were made in the cooperative laboratory maintained by the Imperial Irrigation District.

Field experimental tract No. 1

Field tract No. 1 was located at the University of California's Meloland Experimental Station on U. S. Highway 80, 5 miles east of El Centro, Calif. The tract consists of 18 acres of land which was tiled in 1939. The study involved the measurement of the amounts of saline elements applied to the tract and the amounts removed by the tile-drainage system. Measurements were made for a period of 8 years and 8 months from 1939 to 1948.

These investigations were initiated by the University of California in cooperation with the Imperial Irrigation District and the U. S. Rubidoux Laboratory at Riverside, Calif. In 1942, the Soil Conservation Service took over the work of measuring the tile effluent and the compilation of the data (tables 17, 18, and 19). The drainage flow was measured with a V-notch weir and float recorder. Irrigation water input was measured by a submerged orifice. Water samples were collected weekly, from which a composite was made and analyzed once each month.

During the 8 years and 8 months of operation, the tract of land was cropped to various experimental plantings, mostly flax, barley, and wheat. There was no surface waste of irrigation water during the entire time the experiment was carried out. Leaching was carried on intermittently in the small experimental plots which were not being cropped. It is estimated that only 15 to 20 percent of the 18 acres was leached in any one year, and possibly 75 percent of the area was leached during the 8 years and 8 months that water measurements were carried on. No leach water was wasted.

In table 17, the years 1944, 1945, and 1946 were years of heavy leaching, as are indicated by the large volume of drainage effluent. The percentage of normal discharge from the tile system increased each year. This increase may be due to small channels developing in the soil due to percolation; however, it suggests that tile systems improve in efficiency with age and may be expected to produce more water with succeeding years of operation.

There was a net removal of 312.82 tons of dissolved solids from the 18-acre tract as indicated in table 18. This amounts to 17.4 tons removed per acre. When it is considered that possibly 36 tons of dissolved solids might have been added to the tract if there had been no tile system, the reclamation program looks quite efficient. Table 18 shows that there was considerable base exchange during the study. The carbonates and bicarbonates were tied up, releasing the chlorides and sodium. The large increase in discharge of nitrates may be attributed to the application of fertilizers on the various experimental plots.

Table 19 reveals three significant phenomena which are important in the reclamation of fine-textured saline soils:

1. Some years, the total discharge of saline elements is less than the input.
2. The rate of discharge has varied only slightly through the 8 years and 8 months.
3. The years when there was an excess of discharge of saline elements over input were those in which leaching was practiced on some of the plots.

Thus in fine-textured soils, ordinary irrigations will not tend to move much of the saline concentrations to the tile systems. It requires a prolonged ponding to produce significant changes in the salt balance of the soil profile.

TABLE 17.--Irrigation water applied, and rainfall and discharge from tile system, for the years 1939-48, Meloland Tile Study, Imperial Valley, Calif.

Year	Input			Discharge	
	Irrigation water	Rainfall	Total input	Tile effluent total	Percent discharge
	Acre-feet	*Acre-feet*	*Acre-feet*	*Acre-feet*	*Percent*
1939[1]	25.01	0.00	25.01	0.96	3.8
1940	105.95	7.97	113.92	6.49	5.7
1941	84.68	22.25	106.93	6.52	6.1
1942	70.05	4.53	74.58	5.08	6.8
1943	54.41	11.56	65.97	4.54	6.9
1944	78.68	8.88	87.56	16.69	19.0
1945	82.06	7.36	89.42	18.58	20.8
1946	75.02	3.81	78.83	14.24	18.1
1947	75.76	.62	76.38	6.21	8.1
1948[2]	23.48	0.	23.48	2.41	9.4
Total or mean	675.10	66.98	742.08	81.72	11.0

[1] Includes October, November, and December.
[2] Includes January to June.

TABLE 18.--Salt balance for period October 1939 to June 1948, Meloland Tile Study, Imperial Valley, Calif.

Chemical elements	Total input	Total discharge	Elements removed
	Tons	*Tons*	*Percent*
Dissolved solids	652.90	965.72	148.0
Calcium (Ca)	86.12	69.94	81.1
Magnesium (Mg)	25.91	38.09	147.0
Sodium (Na)	84.18	185.65	220.8
Bicarbonate (HCO_3)	74.73	21.39	28.6
Sulphate (SO4)	275.03	283.77	103.0
Chloride (Cl)	75.96	276.78	364.5
Nitrate (NO_3)	1.54	11.37	737.0

TABLE 19.--Input and discharge of total dissolved solids for the years 1939-48, Meloland Tile Study, Imperial Valley, Calif.

Year	Input	Discharge		
	Dissolved solids	Dissolved solids	Percent discharge	Rate
	Tons	*Tons*	*Percent*	*Tons/Ac.-Ft.*
1939[1]	27.10	11.21	41.4	11.68
1940	121.90	66.87	54.9	10.30
1941	67.96	71.38	105.0	10.95
1942	71.40	56.38	79.0	11.10
1943	41.15	46.61	113.3	10.27
1944	66.66	212.73	319.1	12.75
1945	77.99	231.10	296.3	12.44
1946	76.70	180.30	235.1	12.66
1947	78.14	66.95	85.7	10.78
1948[2]	23.90	22.19	92.8	9.21
Totals or means	652.90	965.72	148.0	11.82

[1] Includes October, November, and December.
[2] Includes January to June.

TABLE 20.--O'Dwyer-Mets Tract--Salinity data, Imperial Valley, Calif., 1946

Time of sampling	Depth of water removed by drainage system	Average salt content of the tile-drainage effluent	Salt removed by the tile system	Average chloride content of the tile-drainage effluent	Chlorides removed by the drainage system
	Feet	*Tons/Acre-feet*	*Tons/Acre*	*Tons/Acre-feet*	*Tons/Acre*
Started leaching August 18, 1946.	0.000	15.30	0.00	3.60	0.00
End of 10 days..	.031	12.65	.37	3.30	.08
End of 20 days..	.119	11.75	1.27	2.90	.35
End of 30 days..	.198	10.50	2.07	2.60	.57
End of 40 days..	.287	9.85	2.88	2.20	.76
End of 50 days..	.370	9.30	3.61	2.00	.95
End of 60 days..	.449	9.10	4.10	2.10	1.07
End of 70 days..	.498	9.05	4.46	1.90	1.16
End of 80 days..	.589	9.00	5.09	1.80	1.31

Field experimental tract No. 2

This tract was located 8 miles southeast of Holtville, Calif., on the O'Dwyer-Mets Ranch. The observations consisted of periodic measurements of the volume of tile-outlet discharge and analyses of water samples over an 80-day leaching period. The tile system consisted of 10,560 feet of 4-inch lateral lines and 1,270 feet of 6-inch collecting lines. The lateral lines are 5.5 feet below ground surface and range in spacing from 160 to 300 feet.

Samples of the tile effluent were taken every 10 days and analysis was made for chlorides and total saline elements (table 20). The volume of flow was measured by bucket and stopwatch. The reduction in chlorides in the drainage water is more marked than the reduction in total saline elements. This is probably due to the greater solubility of the chlorides.

Field experimental tract No. 3

This tract was located on 80 acres of the H. B. Ross Ranch, 6 miles southeast of Holtville, Calif. Observations on the salinity trend of the tile-drainage effluent were made prior to, during, and following a 62-day leaching period. The soils were slowly permeable. The tile-drainage system consists of 14,700 feet of 4-inch lateral lines and 1,350 feet of 6-inch and 800 feet of 8-inch collecting lines. The lateral lines are 5.5 feet below ground surface and are spaced at 300 feet.

Samples of the tile effluent were taken weekly and analysis was made for chlorides and total salts (table 21). The concentration of total salts and chlorides decreased during the leaching period but returned almost to 80 percent of normal after leaching was discontinued.

Field experimental tract No. 4

This tract was located on 60 acres of the W. B. Collins Ranch, 5 miles northwest of Westmoreland, Calif. Observations on the trend of both the salinity of the tile effluent and the movement of saline elements in the 5-foot soil profile were made. Two 30-day leaching periods were analyzed. A tile system consisting of 4,683 feet of 4-inch lateral lines and 2,448 feet of 6-inch collecting lines provided subdrainage for the tract. Spacing of the laterals was 300 feet. The soils were medium-textured in the surface 5 feet, underlain by light textured subsoils.

Soil samples were taken to 5-foot depth prior to leaching, after the first leaching trial, and again at the conclusion of the second 30-day leaching period (table 22).

Field experimental tract No. 5

This tract was located on 52 acres of the Simon Ranch, 3-1/2 miles northeast of Westmoreland, Calif. Observations on the volume and saline concentration of the tile-drainage discharge were made concurrent with analysis of soil samples secured before and after leaching. The drainage system on this tract consists of a series of 4-inch lateral lines spaced at 300-foot intervals with outlet into a 6-inch collecting line. Water was ponded on this field for 84 days. Soil samples were secured at 1-foot intervals to a depth of 4 feet. Measurements of tile—outlet plot indicated that approximately 0.3 acre-foot per acre of leach water percolated to the tile system. This leachate removed approximately 22 tons of saline elements per acre from the tract. At the end of the 84-day period, however, the saline concentration of the tile effluent had not diminished (table 23).

It is evident that while there was some removal of saline elements from the top 2 feet of soil as a result of the leaching, there was no significant change in the third or fourth foot.

Field experimental tract No. 6

This tract was located on 240 acres of the Immel Ranch, 7 miles northeast of Holtville, Calif. Observations were made of the saline concentrations of the tile-drainage effluent and of the changes in saline content of the top 5-foot profile of the soil during a 129-day leaching trial. The tile system has laterals spaced at 250-foot intervals. The soils are moderately permeable to a depth of 9 feet. Flow from the tile system was measured continuously with a recorder. Water samples were collected weekly. A total of approximately 0.70 acre-foot per acre of leach water passed through the soil profile to the tile system during this study. This water removed a total of 53 tons of saline elements per acre from the tract. There was little, if any, change in the saline content of the drainage water during the entire 129-day trial.

Soil samples were secured to a depth of 5 feet at 5 different locations over the tract (table 24). In comparing pre- and postleaching samples, the decrease of saline elements in the upper 2 feet of soil is offset by an increase in the lower 2 feet.

Field experimental tract No. 7

The investigations made on this tract were the most comprehensive field studies of leaching attempted by the project staff. Tract No. 7 is a 160-acre field on the R. B. Wilson Ranch, northwest of Holtville, Calif. The tract was tiled on a 337-foot spacing in 1949 (fig. 21). Accurate measurements of water applied and wasted were made, using wooden Parshall flumes equipped with flow recorders. A tile-effluent recorder was installed on the tile outlet. In addition, a Young-type screen evaporation pan was installed near the north edge of

TABLE 21.--Tile-effluent discharge and saline elements removed during leaching on the H, B. Ross Ranch, Imperial Valley Calif., 1947

Date	Tile discharge	Accumulative discharge per acre	Saline content of drain water	Accumulative saline elements removed per acre	Chloride content of drain water	Chlorides removed per acre	Remarks
1947	*G.P.M.*	*Acre-feet*	*Tons/Ac.-ft.*	*Tons*	*Tons/Ac.-ft.*	*Tons*	
6-27.........	50		22.1		8.9		
7-4..........			24.7		7.6		
7-11.........			17.6		6.7		
7-18.........			20.8		7.6		
7-25.........	27		19.2		7.8		
7-27.........							Leaching water applied
8-1..........	80	0.011	15.0	0.168	5.4	0.067	
8-8..........	150	.034	16.1	.512	6.3	.202	
8-15.........	286	.079	17.0	1.212	6.3	.481	
8-22.........	345	.144	16.4	2.228	5.7	.862	
8-29.........	320	.213	15.6	3.249	5.3	1.230	
9-5..........	320	.279	11.6	4.072	5.0	1.560	
9-12.........	320	.345	13.8	4.837	5.0	1.880	
8-19.........	187	.397	15.9	5.553	5.5	2.147	
9-26.........	120	.429	16.9	6.039	6.0	2.325	Leaching water removed
10-3.........	70	.448	17.5	6.377	6.4	2.447	
10-10........	40	.460	18.0	6.579	6.9	2.522	
10-17	25	.467	18.6	6.704	7.1	2.570	

[1] P.p.m. = Parts per million. [2] T.a.f. = Tons per acre-foot.

TABLE 22.--Concentration of total dissolved solids in soil samples from W. B. Collins Ranch, Imperial Valley, Calif.

PLOT A

Depth of sample	Prior to leaching periods		Following one 30-day leaching period		Following two 30-day leaching periods	
Feet	*P.p.m.*[1]	*T.A.F.*[2]	*P.p.m.*	*T.a.f.*	*P.p.m.*	*T.a.f.*
0-1........................	5,350	10.70	4,010	8.12	2,110	4.22
1-2........................	9,030	18.06	6,560	13.12	5,860	10.12
2-3........................	6,010	12.02	5,370	10.74	5,540	11.08
3-4........................	4,480	8.96	2,550	5.10	2,050	4.10
4-5........................	3,180	6.36	2,180	4.36	3,040	6.08

PLOT B

Depth of sample	Prior to leaching periods		Following one 30-day leaching period		Following two 30-day leaching periods	
0-1........................	7,150	14.30	6,780	13.56	5,490	10.98
1-2........................	10,630	21.26	8,220	16.44	7,610	15.22
2-3........................	8,800	17.60	8,540	17.08	7,190	14.38
3-4........................	6,500	13.00	4,560	9.12	4,380	8.76
4-5........................	6,740	13.48	5,410	10.82	4,490	8.98

TABLE 23.--Chemical analysis of soil samples taken on the Simons Ranch, Imperial Valley, Calif.

BEFORE LEACHING

Depth of sample	Total dissolved solids	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Carbonate and Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (CL)	Nitrate (NO_3)
Feet	*P.p.m.*[1]	*P.p.m.*	*P.p.m.*	*P.p.m.*	*P.p.m.*	*P.p.m.*	*P.p.m.*	*P.p.m.*
0-1..........	23,140	2,570	837	3,100	549	3,960	8,520	22
1-2..........	13,940	1,445	395	2,910	305	5,832	2,660	12
2-3..........	9,610	600	248	3,174	305	2,926	3,195	9
3-4..........	10,850	394	249	3,858	305	1,373	4,793	12
AFTER LEACHING								
0-1..........	6,420	770	48	1,243	427	3,336	710	--
1-2..........	9,290	1,000	48	1,864	244	4,368	1,420	--
2-3..........	9,570	550	63	2,813	275	2,184	3,728	--
3-4..........	10,610	650	72	2,828	218	2,100	4,083	--

[1] P.p.m = Parts per million.

TABLE 24.--Chemical analysis of soil samples taken on Immel Ranch, Imperial Valley, Calif.

BEFORE LEACHING

Depth of sample	Total dissolved solids	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Carbonate and bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)
Feet	*P.p.m.*[1]	*P.p.m.*	*P.p.m.*	*P.p.m.*	*P.p.m.*	*P.p.m.*	*P.p.m.*
0-1....................	47,500	3,700	890	10,180	372	9,336	17,750
1-2....................	28,310	1,800	473	7,009	305	9,048	8,520
2-3....................	18,710	1,560	284	4,213	519	7,248	4,438
3-4....................	13,570	790	234	3,399	244	5,040	3,461
4-5....................	10,440	360	81	1,495	305	3,346	2,574
AFTER LEACHING							
0-1....................	8,450	850	218	1,612	394	4,752	888
1-2....................	16,440	1,190	271	3,559	275	7,656	2,574
2-3....................	20,840	1,570	313	4,662	183	7,512	5,236
3-4....................	24,500	1,490	517	5,812	183	6,552	8,165
4-5....................	18,980	900	345	5,191	183	4,128	7,455

[1] P.p. m. = Parts per million.

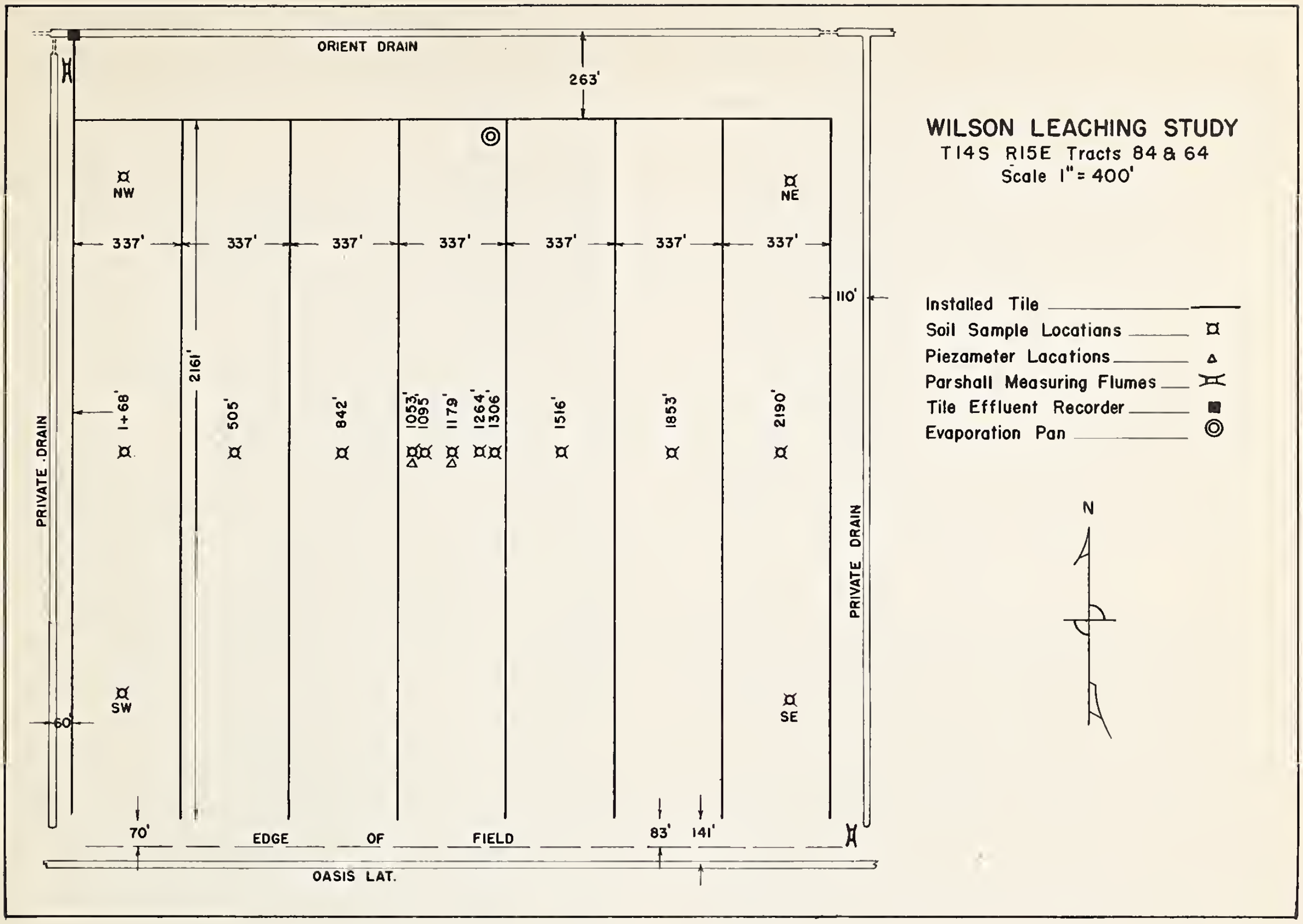
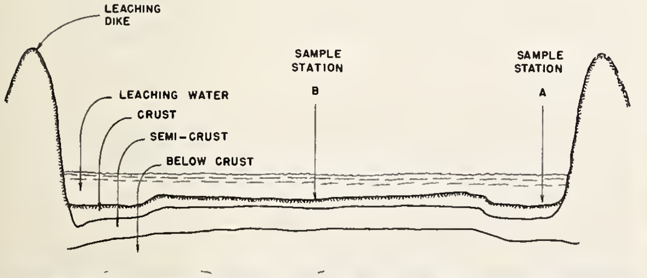
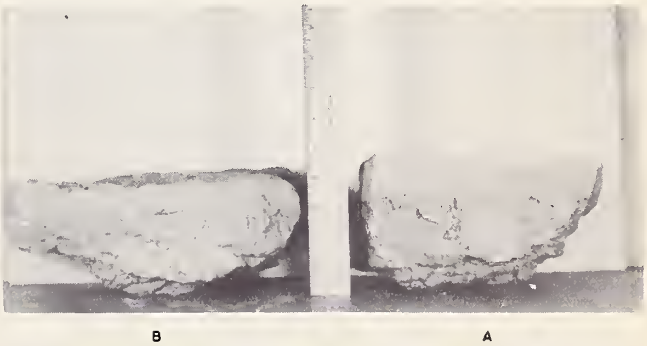


Figure 21.--Map of Wilson tract Imperial Valley, Calif., showing drainage system and location of measuring devices and soil-sample stations.



LEACHING PLOT PROFILE SHOWING THE DEFLOCCULATED SEGREGATED CRUST, THE SEMI-DEFLOCCULATED CRUST AND THE SOIL BELOW THE DEFLOCCULATED SURFACE. SAMPLES FOR PERMEABILITY RUNS AND ANALYSIS WERE TAKEN AT SAMPLE STATIONS "A" AND "B". STATION "A" WAS TAKEN NEXT TO THE LEACHING DIKE AND "B" WAS TAKEN AT A POINT MIDWAY BETWEEN TWO DIKES.



SOIL SAMPLES TAKEN AT SAMPLE STATIONS "A" AND "B". SAMPLE "A" WAS TAKEN NEXT TO A DIKE AND "B" MIDWAY BETWEEN TWO DIKES.

Figure 22.--Location sketch and photograph of two surface soil samples from the Wilson tract, Imperial Valley, Calif.

the tract to record evaporation losses. Samples of the inflow, waste, and tile-drainage water were secured periodically, and of the chemical content analyzed. A series of water-level piezometers was installed adjacent to and out from several tile lines. Soil samples were secured to a depth of 5 feet on each hole prior to each leaching trial and at the conclusion of the study. In addition, 2 holes were bored to 20 feet, and samples were taken in 1-foot increments before each leaching began and at the conclusion of the trials. A total of 410 soil samples was secured and analyzed during this investigation. In all, 5 leaching trials were run on the Wilson tract. Water was ponded for periods ranging from 30 days to 136 days. After each trial, the tract was allowed to dry, and soil samples were secured before proceeding with a new leaching trial. The soils on the Wilson tract have a low permeability as they are quite fine textured throughout the 9-foot profile.

Analysis of data.--A brief analysis of the data in table 25 reveals the following:

(1) A large volume of water was required for these leaching trials. This is probably because large amounts were wasted in order to keep the salt balance in the leaching ponds at a low level. The average waste was 56 percent.

(2) Considerable amounts of saline elements were removed by the surface-waste water. The surface waste carried off an excess of saline elements over the amount applied in all trials except the last one. (The last trial occurred in the spring and summer when excessive evaporation caused leach water to become concentrated and waste was low.)

(3) The rate of daily flow from the tile system did not diminish materially except after the first trial. Peak discharge declined with succeeding trials until the land was disked between the fourth and fifth trials, when peak discharge rose to previous high levels.

(4) The rate of removal of saline elements declined with each succeeding trial, being 28.6 tons per day at the initial trial and only 10.8 tons per day during the fifth trial. Also, the net saline elements removed per acre foot of water used gradually declined with succeeding trials.

(5) The amount of water which was unaccounted for and thus was presumed to have seeped downward and/or away from the tract was, on the average, about 0.24 acre-foot per day. This amount did not vary materially during any of the 5 leaching trials. This volume of seepage compares favorably with the volume of water being drained away by the tile system. It was about two-thirds the amount flowing from the tile system.

(6) The evaporation from the leaching tract was much greater than anticipated. Rates of evaporation were greatest during the summer months.

Table 26 is an analysis of what happened to the water after it was applied to the tract for the 5 different leaching trials. From 90 to 95 percent of the water applied was lost by surface waste and evaporation, and only 5 to 10 percent passed through the soil as leaching water.

Soil-sample analysis.--A study was made of the movement of the saline elements during the five leaching trials on the Wilson tract. An attempt was also made to determine the effect of the tile lines on this displacement of elements. Due to curtailment of the work, it was not feasible to analyze every sample secured. Thus, the work was concentrated on getting data on the preleaching and the postleaching samples. However, the samples from the five stations adjacent to and out from the tile laterals were analyzed for each leaching trial.

Table 27 is a calculation of the percentage of saline elements remaining in the soil profile following each leaching trial on the Wilson tract. This analysis was made of soil samples from the five stations near the center of the tract which were adjacent to and near the midpoint between tile lines. It is easy to see that the greatest percentage of removal of saline elements occurs near the tile lines, while at the midpoint there is little or no overall reduction in concentration of saline elements.

Tables 28 and 29 are summaries of the complete chemical analyses on the preleaching and postleaching soil samples from the two 20-foot sampling stations on the Wilson tract. The data from table 28 are from a sampling site adjacent to a tile lateral while the data from table 29 are from a sampling site midway between tile laterals. Comparison of these data reveals that the leaching of calcium, sodium, and chlorides was more effective near the tile lateral.

A study was made of the surface soil characteristics in the leach plots. A fine-textured deflocculated soil surface condition was formed during the leaching trials (fig. 22). The wave action in the leaching dikes tends to stir up the top layers of the soil, forming a surface layer of very fine textured silt. This silt layer influences infiltration rates and should be destroyed by disking the surface 6 inches of the leach plots between subsequent leaching periods.

Water-table data.--A battery of piezometers was installed at both stations 11 + 28 and 11 + 79. These piezometers were installed at depths of 5, 10, and 15 feet. The observation of water-table depth at station 10 + 28, adjacent to the tile line, indicated that both when water was ponded and when the plots were dry, the movement of ground water was down from the top and up from below to the tile line. However, at station 11 + 79, midway between tile lines, the movement of water was always down during leaching, indicating that the disposition of water due to deep seepage may have all occurred near the midpoint between tile lines while the tile effluent originated for the most part at or near the tiles.

Item		First run	Second run	Third run	Fourth run	Fifth run
		Dates	*Dates*	*Dates*	*Dates*	*Dates*
Water applied		3-3-49	5-15-49	7-19-49	12-26-49	4-18-50
Water turned off		4-1-49	6-30-49	10-1-49	2-11-50	8-31-50
Surface waste started flowing		3-14-49	5-26-49	7-29-49	1-6-50	5-9-50
Surface waste stopped flowing		4-15-49	7-2-49	10-9-49	2-18-50	9-19-50
Tile-discharge increase		3-4-49	5-18-49	7-21-49	12-28-49	4-20-50
Tile discharge to normal		5-12-50	7-21-49	11-20-49	4-2-50	10-14-50
Peak-tile discharge occurred		4-1-49	6-25-49	8-7-49	1-1-50	7-27-50
Peak-saline concentration occurred		4-29-49	6-3-49	8-12-49	3-31-50	4-21-50
Preleaching soil sampling		3-1-49	5-6-49	7-18-49	12-2-49	4-13-50
Postleaching soil sampling		5-6-49	7-18-49	12-2-49	4-13-50	10-31-50
	Units	*Results*	*Results*	*Results*	*Results*	*Results*
Net area leached	Acres	140	140	140	140	140
Duration of leaching	Days	30	46	74	48	136
Total water applied	Acre-feet	188	394	827	418	1,136
Total salts applied in water	Tons	243	493	1,254	589	1,610
Total water surface wasted	Acre-feet	63	224	553	337	506
Total salts surface wasted	Tons	380	852	1,576	733	1,263
Total water from tile system	Acre-feet	14.1	13.8	24.6	14.9	45.2
Total salts removed by tile system	Tons	858	864	1,288	686	1,463
Average daily tile flow	Acre-feet	0.47	0.31	0.33	0.31	0.33
Rate of salt removed per day by tile system	Tons	28.6	18.8	17.4	14.3	10.8
Peak-tile discharge	G. p. m.	79	86	73	49	86
Peak-saline concentration of effluent	T./ac-ft	66	68	55	49	49
Total net salts removed from plot	Tons	895	1,224	1,609	830	1,115
Net salts removed per acre	Tons	6.4	8.7	11.5	5.9	8.0
Net salts removed per acre foot of water used	Tons	4.7	3.1	1.9	2.0	1.0
Total evaporation from plot	Acre-feet	103	147	229	55	554
Water computed to deep seepage	Acre-feet	8	9	20	11	31
Evaporation per day	Acre-feet	3.4	3.4	3.1	1.2	4.1

TABLE 25.--Summary of five leaching tests on the R. B. Wilson Plot, Imperial Valley, Calif.

TABLE 26.--Disposition of leaching water for the five leaching trials on the R. B. Wilson Tract, Imperial Valley, Calif.

Item	Trial No. 1		Trial No. 2		Trial No. 3		Trial No. 4		Trial No. 5	
	Acre-feet	*Percent*[1]	*Acre-feet*	*Percent*[1]	*Acre-feet*	*Percent*[1]	*Acre-feet*	*Percent*[1]	*Acre-feet*	*Percent*[1]
Water applied.......	188	100	394	100	827	100	418	100	1,136	100
Surface waste.......	63	33.5	224	57.0	553	67.0	337	81.0	506	44.3
Tile drainage[2]......	14	7.5	14	3.5	25	3.0	15	3.5	45	4.0
Evaporation.........	103	55.0	147	37.2	229	27.7	55	13.0	554	49.0
Deep seepage[3].......	8	4.0	9	2.3	20	2.3	11	2.5	31	2.7

[1] Percent of the water applied.
[2] Approximate to nearest acre-foot.
[3] Residual estimate, not measured.

TABLE 27.--Percentages of soluble salts remaining in the soil after each leaching trial, Wilson Ranch, Imperial Valley, Calif.

Depth of sampling	Station 10+53 42 feet from the tile line	Station 10+95 84 feet from the tile line	Station 11+79 midpoint between tile line	Station 12+64 84 feet from the tile line	Station 13+06 42 feet from the tile line	Remarks
Feet	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	
0-1.................	59	94	113	74	97	After 1st leaching
	37	48	60	36	58	After 2nd leaching
	40	44	81	58	55	After 3rd leaching
	7	51	42	44	52	After 4th leaching
	36	34	17	50	42	After 5th leaching
1-2.................	141	142	110	68	101	After 1st leaching
	72	92	102	69	84	After 2nd leaching
	70	56	128	52	80	After 3rd leaching
	50	67	62	42	72	After 4th leaching
	66	24	32	48	31	After 5th leaching
2-3.................	103	122	110	95	100	After 1st leaching
	102	63	90	58	74	After 2nd leaching
	70	98	127	97	65	After 3rd leaching
	70	69	70	71	61	After 4th leaching
	80	65	26	79	42	After 5th leaching
3-4.................	138	104	89	120	110	After 1st leaching
	125	61	111	59	88	After 2nd leaching
	78	95	130	85	77	After 3rd leaching
	77	92	119	65	62	After 4th leaching
	106	63	66	71	56	After 5th leaching
4-5.................	130	143	93	190	89	After 1st leaching
	136	114	77	141	77	After 2nd leaching
	154	161	124	188	87	After 3rd leaching
	96	118	121	110	67	After 4th leaching
	122	114	91	133	70	After 5th leaching

TABLE 28.--Analysis of soil samples taken from station 10 + 28 - adjacent to tile-drainage lateral R. B. Wilson Ranch, Imperial Valley, Calif., 1949

Depth of sample	Dissolved solids	Calcium (Ca)		Magnesium (Mg)		Sodium (Na)		Bicarbonate (HCO_3)		Sulfate (SO_4)		Chloride (Cl)	
Feet	T.a.f.[1]	M.e.l.[2]	P.p.m.[3]	M.e.l.[2]	P.p.m.[3]	M.e.l.[2]	P.p.m.[3]	M.e.l.[2]	P.p.m.[3]	M.e.l.[2]	P.p.m.[3]	M.e.l.[2]	P.p.m.[3]
PRIOR TO LEACHING--MARCH 3, 1949													
0-2..........	56.88	200.92	4,018	90.72	1,107	194.86	4,482	8.00	488	108.50	5,208	370.00	13,135
2-4..........	38.89	74.72	1,494	61.62	752	197.67	4,546	4.50	275	54.51	2,616	275.00	9,763
4-6..........	30.19	35.04	701	41.32	504	177.57	4,084	4.00	244	54.93	2,637	195.00	6,923
6-8..........	28.41	34.68	694	30.54	373	161.16	3,707	5.00	305	101.38	4,866	120.00	4,260
8-10.........	29.96	30.76	615	26.59	324	174.07	4,004	4.75	290	141.66	6,800	85.00	2,947
10-12.........	29.90	58.63	1,173	29.10	355	144.10	3,314	5.50	336	138.83	6,664	87.50	3,106
12-14.........	28.43	36.11	722	24.25	296	157.70	3,627	5.50	336	135.06	6,483	77.50	2,751
14-16.........	29.82	43.26	865	26.77	327	158.39	3,643	6.00	366	144.92	6,956	77.50	2,751
16-18.........	36.03	74.00	1,480	37.91	463	164.64	3,787	5.50	336	186.05	8,930	85.00	3,018
18-20.........	30.44	82.58	1,652	31.08	379	119.33	2,745	5.50	336	162.49	7,800	65.00	2,308
FOLLOWING FIFTH LEACHING PERIOD--Oct. 30, 1950													
0-2..........	12.08	41.27	829	22.99	280	28.08	646	6.00	366	67.79	3,254	18.75	666
2-4..........	16.34	36.82	736	25.87	316	60.41	1,389	4.00	244	100.35	4,817	18.75	666
4-6..........	27.09	55.41	1,108	41.14	502	120.02	2,760	3.75	229	111.32	5,343	101.50	3,603
6-8..........	27.57	47.53	951	37.73	460	150.21	3,455	3.00	183	38.74	1,860	193.75	6,875
8-10.........	26.33	46.12	922	41.86	511	138.26	3,180	2.75	168	35.99	1,728	187.50	6,656
10-12.........	29.60	61.49	1,230	46.71	570	136.61	3,142	3.25	198	86.56	4,155	155.00	5,503
12-14.........	38.67	92.95	1,859	48.69	594	166.27	3,824	2.25	137	165.66	7,952	140.00	4,970
14-16.........	38.13	158.37	3,167	49.58	605	87.29	2,008	5.25	320	213.74	10,260	76.25	2,707
16-18.........	36.51	120.12	2,402	49.04	598	107.39	2,470	4.50	275	228.30	10,958	43.75	1,553
18-20.........	36.87	89.38	1,788	31.44	384	152.44	3,506	3.75	229	236.96	11,374	32.50	1,154

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[1] T.a.f. = Tons per acre-foot.
[2] M.e.l. = Milligram equivalents per liter.
[3] P.p.m. = Parts per million.

TABLE 29.--Analysis of soil samples taken from station 11 + 79 - midway between tile-drainage laterals, R. B. Wilson Ranch, Imperial Valley, Calif, 1949

Depth of sample	Dissolved solids	Calcium (Ca)		Magnesium (Mg)		Sodium (Na)		Bicarbonate (HCO_3)		Sulfate (SO_4)		Chloride (Cl)	
Feet	*T. a. f.*[1]	*M.e.l.*[2]	*P.p.m.*[3]	*M.e.l.*[2]	*P.p.m.*[3]	*M.e.l.*[2]	*P.p.m.*[3]	*M.e.l.*[2]	*P.p.m.*[3]	*M.e.l.*[2]	*P.p.m.*[3]	*M.e.l.*[2]	*P.p.m.*[3]
PRIOR TO LEACHING--Feb. 28, 1949													
0-2..........	49.37	241.67	4,833	66.11	807	95.38	2,194	16.00	976	171.66	8,240	215.00	7,633
2-4..........	29.95	63.99	1,280	34.31	419	157.57	3,394	6.00	366	79.87	3,834	160.00	5,680
4-6..........	23.48	38.61	772	29.82	364	114.60	2,636	6.75	412	103.78	4,981	72.50	2,574
6-8..........	17.15	21.45	429	22.46	274	84.88	1,952	6.25	381	95.04	4,562	27.50	976
8-10..........	14.21	15.73	315	18.32	224	73.05	1,680	6.75	412	72.85	3,497	27.50	976
10-12..........	12.62	15.73	315	16.17	197	62.76	1,443	9.50	580	60.16	2,888	25.00	888
12-14..........	23.53	49.34	987	29.82	364	96.31	2,215	6.75	412	143.72	6,899	25.00	888
14-16..........	31.69	88.66	1,773	40.78	498	106.88	2,458	6.50	397	204.82	9,831	25.00	888
16-18..........	23.99	53.98	1,080	31.80	388	94.01	2,162	6.00	366	146.29	7,022	27.50	976
18-20..........	17.35	29.67	593	21.02	256	79.19	1,821	6.50	397	98.38	4.722	25.00	888
FOLLOWING FIFTH LEACHING PERIOD--Oct. 30, 1950													
0-2..........	15.59	29.67	593	19.76	241	72.94	1,678	11.00	671	52.62	2,526	58.75	2,086
2-4..........	16.77	23.95	479	19.40	237	91.42	2,103	5.25	320	52.02	2,497	77.50	2,751
4-6..........	26.27	33.96	679	32.52	397	149.07	3,429	5.00	305	68.05	3,266	142.50	5,059
6-8..........	20.30	28.60	572	26.59	324	106.37	2,447	4.00	244	77.56	3,723	80.00	2,840
8-10..........	30.31	27.17	543	22.10	270	105.48	2,426	4.00	244	105.75	5,076	45.00	1,598
10-12..........	18.28	24.31	486	21.20	259	92.60	2,130	5.50	336	97.61	4,685	35.00	1,243
12-14..........	28.03	67.21	1,344	36.47	445	108.51	2,496	6.00	366	163.69	7,857	42.50	1,509
14-16..........	35.41	111.90	2,238	47.97	585	109.58	2,520	4.00	244	215.45	10,342	50.00	1,775
16-18..........	21.42	37.54	751	26.23	320	102.47	2,357	4.00	244	102.24	4,908	60.00	3,130
18-20..........	23.63	62.21	1,244	31.08	379	88.72	2,041	5.50	336	124.01	5,952	52.50	1,864

[1] T.a.f. = Tons per acre-foot. [2] M.e.l. = Milligram equivalents per liter. [3] P.p.m. = Parts per million.

Laboratory-Leaching Studies

The laboratory-leaching studies were not carried out as extensively as the field studies, but sufficient data were recorded on the various laboratory phases to determine the value of each method. The laboratory work consisted of the following:

(1) Gypsum-impregnated water was used in an effort to replace exchangeable sodium and increase the infiltration rate and permeability of fine-textured saline soils.

(2) Detergent-impregnated water was used as a wetting agent in an effort to increase the infiltration rate and permeability of fine-textured saline soils.

(3) A series of 6-foot long, 10-inch diameter, galvanized iron tanks was used to determine permeability of stratified soils and to test theories on reducing the leaching time required to reclaim a given soil.

Gypsum studies

A number of slowly permeable, inplace, soil samples were brought into the laboratory, and permeability studies, using the falling-head permeameter, were made with both irrigation water and irrigation water containing 0.1 percent of gypsum (CaS04). Gypsum impregnated water was used in an effort to replace exchangeable sodium and to increase the permeability of fine-textured soils.

Two types of soils were used in the test, one having a permeability of 0.08 and the other 4.4 cubic centimeters per square centimeter per hour. Four replicates were run of each soil to determine the effect of the gypsum. After the permeability had become stabilized, the permeameter using irrigation water in the test was drained and gypsum impregnated water applied in the permeameter. There was no increase in the permeability of either the moderately or slowly permeable soil samples. The permeability results indicate that the application of gypsum to the Imperial Valley soils may have no appreciable effect upon the rate of infiltration or the permeability. This statement is further substantiated by the fact that gypsum crystals are commonly found in the subsoils of the Valley.

Detergent studies

A number of slowly permeable, inplace, soil samples were brought into the laboratory and permeability studies, using the falling-head permeameter, were made with both irrigation water containing 0.1 percent of sulphonated ester of ethel alcohol. The soil used in the study was a heavy clay soil which was highly saline.

The samples tested with irrigation water had permeability rates so low that they could not be measured in the falling-head permeameter. The samples tested with detergenated impregnated water had permeability rates which ranged from 0.004 to 0.14 cubic centimeters per square centimeter per day during a 28-day run. Analysis of the soil columns after the permeability tests were terminated revealed that there were no apparent leaks or channels in the samples.

In conjunction with the permeability studies, a study was made of the toxic effect of detergents on crop growth. Detergents definitely appear to be quite toxic to plants. This is rather important, since a large amount of detergents could be absorbed by the soil during leaching and might prove as harmful as the saline elements which are being removed. The increase in permeability is apparent, but it would be offset by the high cost of the detergents and the toxic effects. The use of detergent in the leaching water also reduces the water's ability to absorb salt as it moves through the soil.

Laboratory-tank studies

A series of 6-foot long, galvanized iron tanks, 10 inches in diameter, was used in the laboratory-leaching study. The tanks were provided with drain openings in the bottom and manometer tubes along the sides at 1-foot intervals. The manometer tubes were used to determine the permeability of the 5.5-foot column of soil. A 1-inch thick steel grill was placed in the bottoms of the tanks to act as drains. These grills were covered with 1/4-inch meshed hardware screens and fine-meshed copper screens to prevent the soil in the bottoms of the tanks from passing out the bottom drains. A 1-inch layer of sand was placed on the screens to act as a filter. Various soils were then carefully packed into the tanks, and water was introduced at the top. A chemical analysis was made of the soils prior to and following leaching (table 30). Analysis was also made of the leaching and drainage-effluent water. These analyses consisted of measuring total dissolved salts and total chlorides. The soils were analyzed for permeability and texture before being placed in the tanks.

The following information was gained from the leaching runs in the laboratory tanks.

(1) Leaching is accomplished in a very short period of time. Large amounts of water can be drained through the tanks because the drain is effective over the entire bottom of the soil column.

(2) Almost complete leaching of saline elements can be accomplished in from 4 to 10 days in the tanks. Similar field-leaching studies require 30 to 300 days for a partial leaching of saline elements.

(3) The salinity trend of the tile-drainage effluent closely approximates the drainage effluent from the laboratory tanks.

(4) The tank studies indicates that 1 foot of water percolating the soil will reclaim light soils and 2 feet of water will be required on fine-textured soils.

Comparison of All Leaching Studies

One of the most revealing comparisons to be made in reviewing all the data on the various

TABLE 30.--Results of two laboratory-leaching studies, made with regular irrigation water, Imperial Valley, Calif.

Item	Units	Sample No. 26 Immel Ranch	Sample No. 27 Wright Ranch
Soil permeability	Cc./Sq./Cm./Hr.	0.55	1.50
Leaching time	Days	11.00	4.00
Water applied	Feet	28.50	31.10
Chlorides in soil			
Before leaching	Tons/ac.-ft.	1.30	.65
After leaching	Tons/ac.-ft.	.04	.002
Total dissolved salts			
Before leaching	Tons/ac.-ft.	21.64	11.46
After leaching	Tons/ac.-ft.	1.62	1.56

leaching studies made in the Imperial Valley deals with the relationship between the amount of water leached through the soil and the rate of removal of saline elements (table 31). In all the studies, the quantity of water removed by the drains was measured and reduced to the equivalent depth of water over the entire area. At the same time, samples of this water were periodically analyzed for total salts and for chloride content. The contrast, in table 31, between the laboratory studies where a total of 2 feet depth of water was passed through the soil, and the field studies where less than 1-foot depth was passed through the profile indicates the desirability of running tank studies.

Figure 23 is a series of curves drawn by plotting the ratio of depth of water percolating through the soil, in feet, to the saline elements removed, tons per acre, in the leaching studies. These curves fall in an interesting pattern. They suggest that the end point of leaching coarse-textured soils might be reached when approximately 1/2-foot to 1-foot of water has been leached through the soil profile to the drain. The end point for leaching fine-textured soils may be reached when approximately 1 to 2 feet of water passes through the profile to the drain.

Cost of leaching

Whether a program of leaching and reclamation is successful depends on how much benefit can be realized from the expenditure of time and money. There are various cost items which must be considered in any leaching program. These are broken down as follows:

1. Cost of land leveling.
2. Cost of surface drainage.
3. Cost of subsurface drainage.
4. Cost of actual leaching.

Land leveling.--Before any leaching is attempted, the land should be leveled and graded so that the leach water can be applied evenly over the field. A compilation has been made of cost data on land-leveling work on 243 farms in the Imperial Valley for the year 1950. It was found that 3,885,481 cubic yards of earth were moved on 14,799.6 acres of land, or an average of 263 cubic yards per acre, at an average cost of 15.9 cents per cubic yard, or about $42.00 per acre.

Surface drainage.--Deep, open drains are an integral part of any leaching program. Provision must be made for the removal of both surface waste and subsurface tile flow. In most cases in the Imperial Valley, an open drain is available. If not, the construction costs will average about $5,000 per mile.

Subsurface drainage.--It has been pointed out that good subsurface drainage, either natural or with tile lines, is required to effectively reclaim lands by ponding and leaching. The following tabulation indicates the cost per foot of installing draintile at a depth of 6.5 feet in the Imperial Valley:

4-inch tile -	$0.31 per foot
5-inch tile -	.33 per foot
6-inch tile -	.36 per foot
8-inch tile -	.44 per foot
10-inch tile -	1.00 per foot

This includes the cost of materials, labor, and completed installation, including a gravel envelope. The average cost for a tile system will be about $50.00 per acre, depending on soil type and tile spacing.

Actual leaching cost.--In addition to the land-leveling and drainage costs, there are a number of other cost items which must be accounted for as follows:

1. Engineer costs (dike locations)	$2.50 per acre
2. Construction of contour dikes	5.00 per acre
3. Subsoiling fine-textured soils	5.00 per acre
4. Control boxes between dikes	1.00 per acre
5. Gate charge for water delivery (estimate)	1.00 per acre
6. Labor for attendant (estimate)	1.00 per acre
7. Smoothing out dikes	5.00 per acre
8. Land leveling (level touchup)	5.00 per acre

TABLE 31.--Comparison of leachate from laboratory and field-leaching studies, Imperial Valley, Calif.

Water removed by the drainage system	Tons per acre of saline elements removed by the drainage effluent													
	Laboratory studies				Field leaching studies									
	Immel		Wright		O'Dwyer		Ross		Simons		Immel		Wilson
Ac.-ft./Acre	*T.d.s.*[1]	*Cl.*[2]	*T.d.s.*[1]	*Cl.*[2]	*T.d.s.*[1]	*Cl.*[2]	*T.d.s.*[1]	*Cl.*[2]	*T.d.s.*[1]	*Cl.*[2]	*T.d.s.*[1]	*Cl.*[2]	*T.d.s.*[1]
0.0	97	50	48	21	13	4	19	8	46	30	62	25	69
.1	95	43	46	19	10	3	16	6	64	26	59	28	68
.2	94	39	45	18	10	3	16	5	55	25	61	29	68
.3	92	34	43	17	9	2	12	5	53	29	62	30	60
.4	90	31	41	16	8	2	16	6			67	30	53
.5	88	27	38	16	8	2	19	7			65	29	49
.6	86	24	35	15	8	2					65	29	49
.7	84	21	30	15							65	29	49
.8	81	18	28	13									49
.9	78	16	27	12									
1.0	75	14	26	11									
1.1	70	12	23	11									
1.2	65	10	20	10									
1.3	60	9	17	9									
1.4	52	7	15	8									
1.5	40	6	13	8									
1.6	22	4	12	7									
1.7	18	3	11	6									
1.8	16	2	10	5									
1.9	14	2	9	4									
2.0	12	1	8	4									

[1] T.d.s = Total dissolved solids.
[2] Cl. = Chlorides.

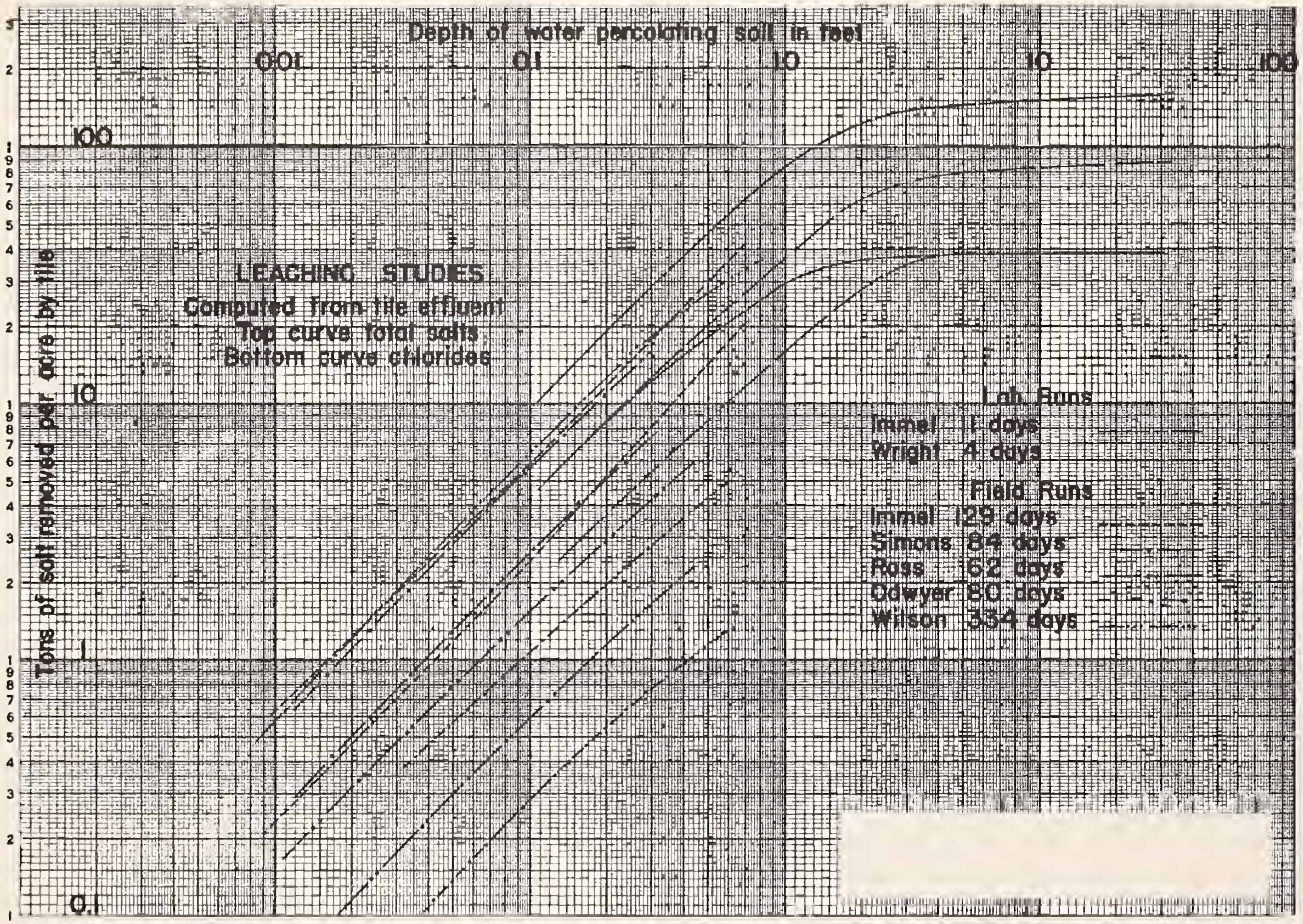


Figure 23.--Leaching studies, computed from tile effluent.

9. Replacing lost soil nutrients	$6.00 per acre
Total costs	$31.50 per acre

Summary of leaching costs. --In making a summary estimate of per-acre costs of leaching it should be recognized that each reclamation project will have physical factors which would add to or eliminate one or more of the following items from the total estimated costs:

1. Land leveling	$42.00 per acre
2. Surface drainage	10.00 per acre
3. Subsurface drainage	50.00 per acre
4. Leaching costs	31.50 per acre
Total estimated costs	$133.50 per acre

Leaching illustrations

A typical leaching operation is shown in figure 24, top. The land is relatively level and permits the construction of straight leaching dikes. The dikes average 5 feet in bottom width, 2 feet wide at the top, and were about 2 feet high. The leaching water averaged 1 foot in depth over the plots. A typical control box used in regulating the depth of water in the leaching ponds is shown in figure 24, bottom. The control boxes are generally made of redwood. They are made in various sizes depending on the size of the area being leached. Gate boards are used to regulate the depth of water in the ponds.

Two examples of leaching-dike construction are shown in figure 25. If the land has a uniform slope, the dike can be constructed in a straight line as shown in figure 25, top. The spacing of the dikes will be dependent upon the slope of the land. If the land is fairly uneven, dikes similar to the ones shown in figure 25, bottom, will be required. The dikes shown in both examples are constructed on the contour to maintain an average leaching-water depth of 1 foot in the pond.

LITERATURE CITED

(1) Christiansen, J. E.
1943. Ground Water Studies in Relation to Drainage. Agr. Engin. Vol. 24, No. 10

(2) ―――――
1945. Measuring Water for Irrigation. Univ. of Calif. Agr. Expt. Sta. Bul. 588.

(3) Darcy, H.
1856. Les Fontaines Publiques, De La Ville de Dijon.

(4) Donnan, W. W.
1946. Model Tests of a Tile Spacing Formula. Soil Sci. Soc. Amer. Proc. 11: 131-136.

(5) ―――――, Aronovici, V. S., and Fox W.W.
1944. The Imperial Valley Soil Sampling Apparatus. Soil Sci. Soc. Proc. Vol. 8.

(6) ―――――, and Christiansen, J. E.
1944. Ground Water Determinations. Western Constr. News. Vol. 19, No. 11.

(7) Hayden, T. A.
1926. Weir Stick for Use in Narrow Canals and Streams. Engin. News Rec. 96:850.

(8) Israelsen, O. W.
1932. Irrigation Principles and Practices. Chap. 11. John Wiley & Sons.

(9) ―――――
1932. Irrigation Principles and Practices. p. 55. John Wiley and Sons.

(10) Kirkham, D.
1949. Flow of Water into Drain Tubes in Soil Overlying an Impervious Layer. Amer. Geophy. Union, Trans. Vol. 30, No. 3.

(11) Kocher, A. E., Carpenter, E. J. and Dean, W. C.
1923. Soil Survey of the Browley Area, California. Univ. of Calif. Agr. Expt. Sta.

(12) Lippicott, J. B.
1929. Hydraulic Measuring Stick. Western Constr. News. 4:424.

(13) McLaughlin, W. W., and Israelsen, O. W.
1932. Drainage of Land Overlying an Artesian Ground Water Reservoir. Utah Agr. Expt. Sta. Bul. 242.

(14) Rohwer, C.
1942. Use of Current Meters in Measuring Pipe Discharges. Colo. St. Coll. Agr. Expt. Sta. Bul. 29.

(15) Schlick, W. J.
1918. Spacing and Depth of Laterals in Iowa Under-Drainage Systems and the Rate of Run-off from Them. Iowa Engin. Expt. Sta. Bul. 52.

(16) Simplex Valve and Meter Co.
1946. The Simplex Type S Parobolic Flume. Bul. 210.

(17) Strahorn, A. T., Watson, E. B., Kocher, A. E., and Echmann, E. C.
1922. Soil Survey of the El Centro Area California. Univ. of Calif. Agr. Expt. Sta.

(18) Tolman, C. F.
1937. Groundwater, McGraw-Hill, Inc.

(19) Wenzel, L. K.
1942. Methods of Determining Permeability of Water-Bearing Materials, with Special Reference to Discharging Well Methods. U. S. Geol. Surv. Water Supply Paper 887.

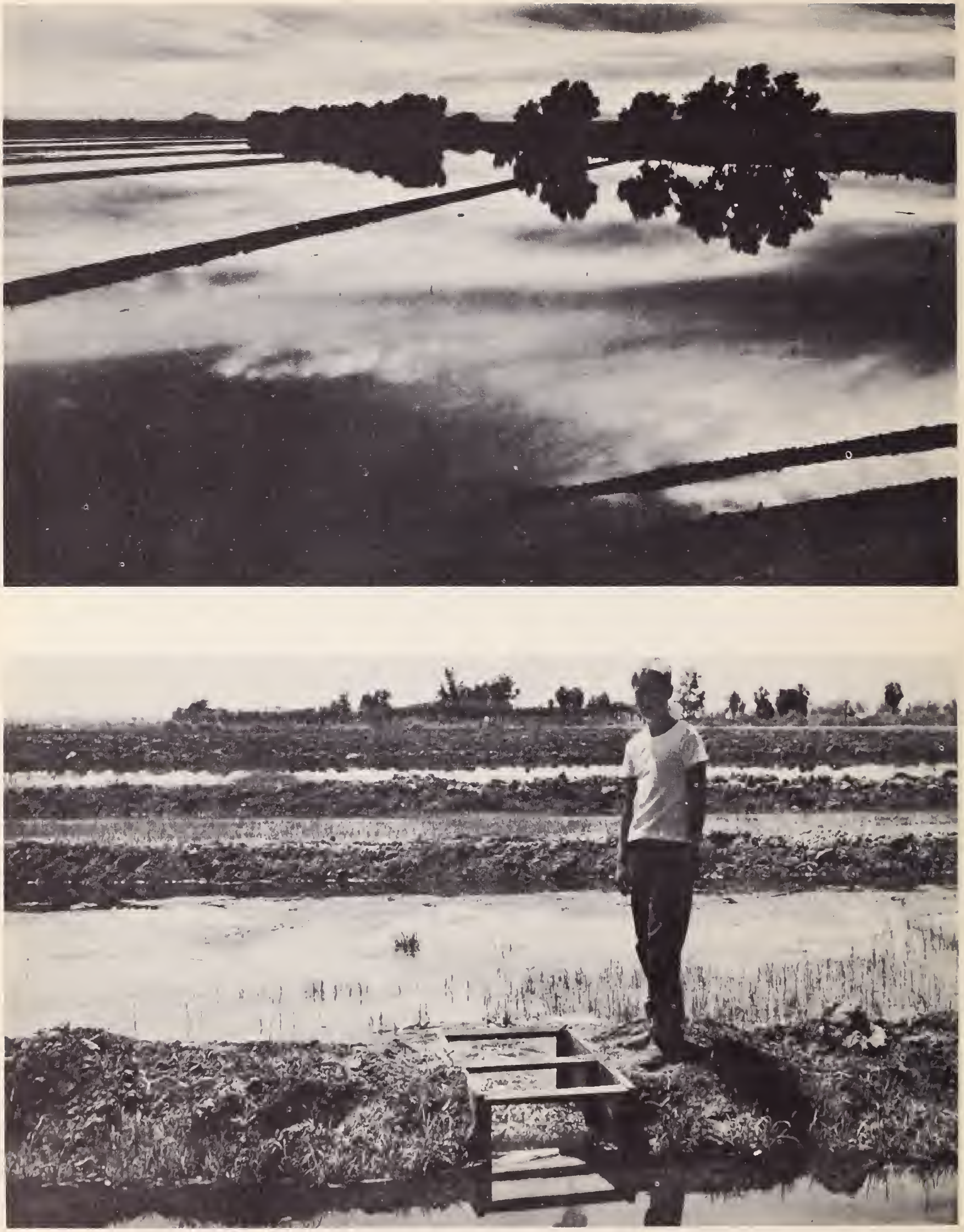
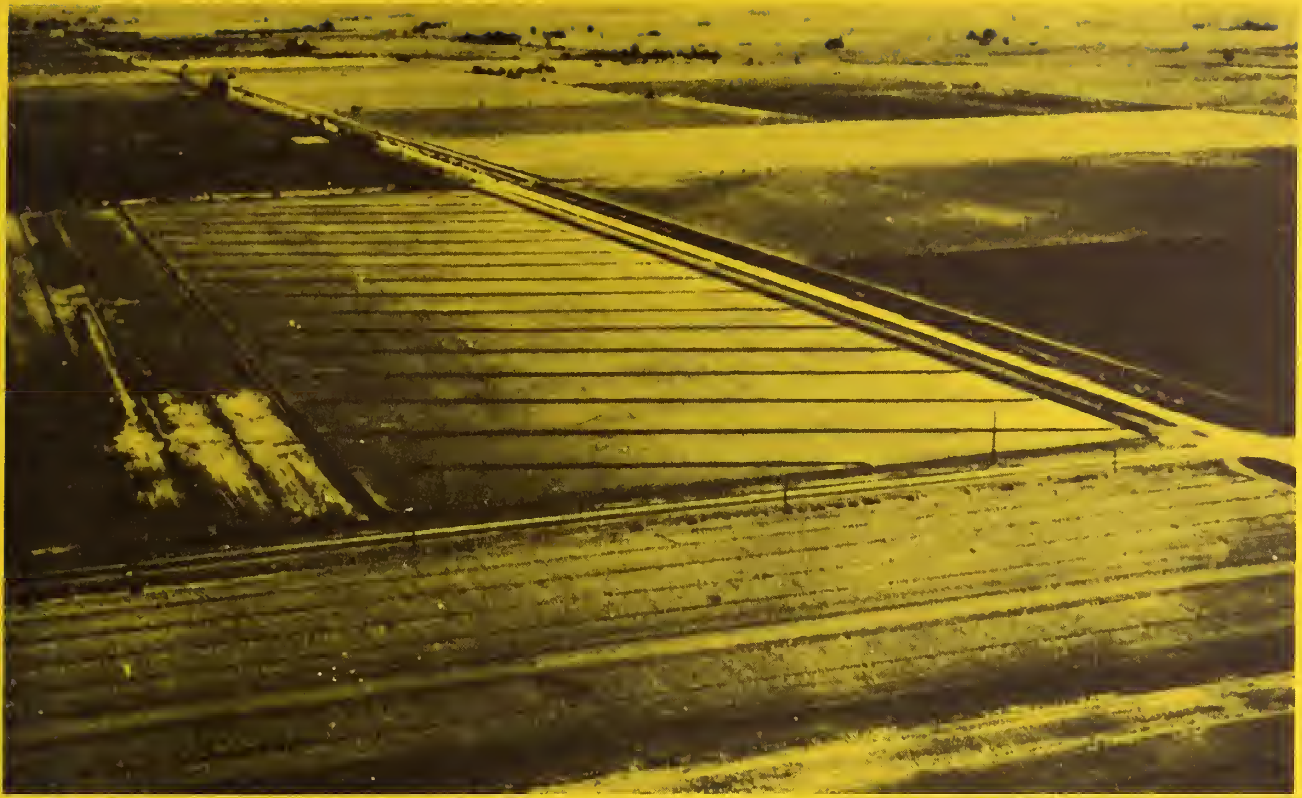


Figure 24.--Top, leaching ponds on a 160-acre tract in Imperial Valley, Calif.; Bottom, dikes and control box used to regulate depth of water in the leaching ponds



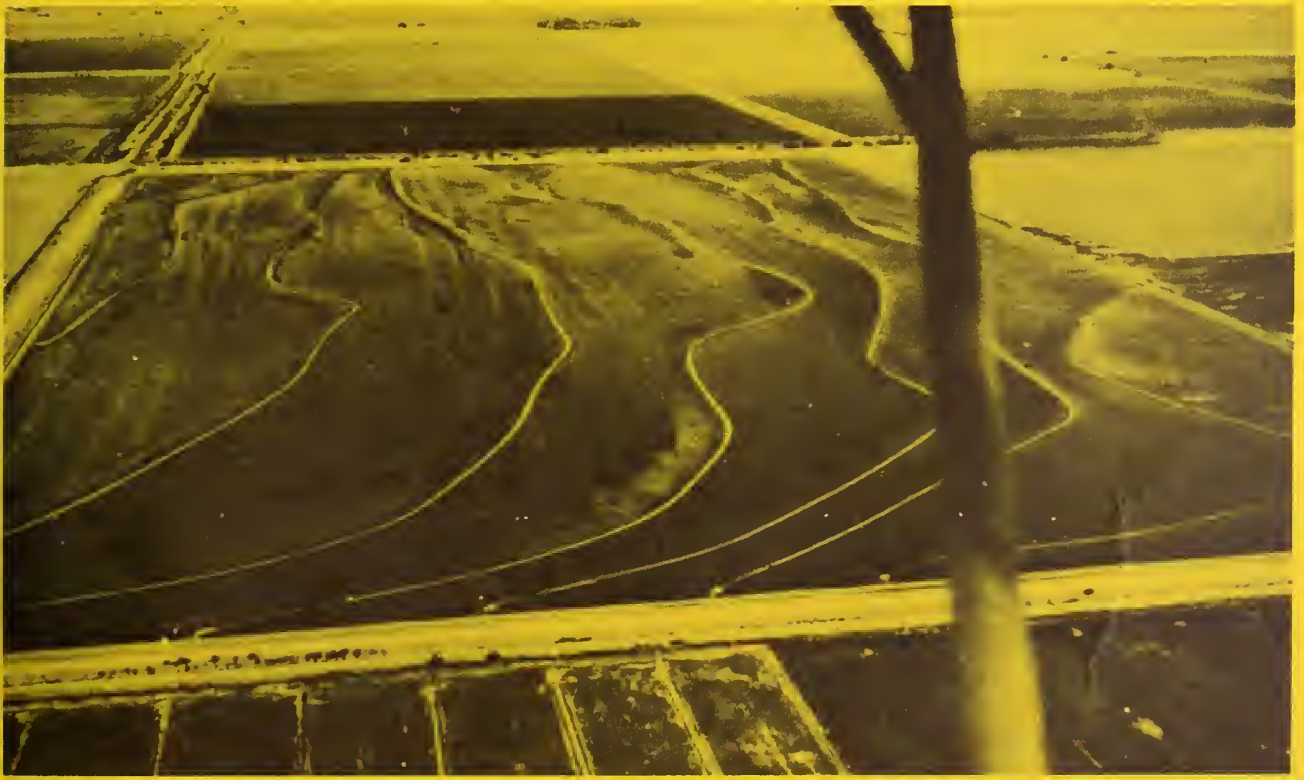


Figure 25.--Imperial Valley, Calif.: Top, leaching operation on well-leveled land with uniform slope; Bottom, leaching operation on land using contour dikes.

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